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PRE- AND POSTINJURY NEUROCOGNITIVE FUNCTIONING OF ADOLESCENT FINNISH ATHLETES – ACUTE SIGNS OF CONCUSSION AND MODIFYING FACTORS

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ACADEMIC DISSERTATION

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ABSTRACT

Concussion is a common injury in high velocity sports such as ice hockey. The importance of appropriate identification, evaluation and management of concussions has been emphasized to avoid more severe injuries and long-term consequences and premature retirements. Adolescent athletes are more prone to concussion than adults, and concussion may cause severe acute and long-term complications in the developing athletes. The initial recognition and evaluation of concussion occurs acutely on the scene of injury. Some observable on-field signs that are thought to indicate concussion diagnosis are loss of consciousness (LOC), amnesia, disorientation, postural instability, and vacant look. A multifaceted approach is recommended for concussion evaluation. The neuropsychological assessment is mentioned as the "cornerstone" of concussion management even if it is insufficient alone. It is important to model the typical cognitive performance and development and to provide reference values for clinicians in order for them to identify atypical brain function after injury. The general aim of the present study was to examine the cognitive performance and post-injury cognitive decline of adolescent athletes. The study's objective was to explore the association between on-field signs of concussion and postinjury neurocognitive deficits. An additional aim was to examine the modifying factors in concussion assessment such as age, concussion history, learning disability and repeated testing.

This thesis comprises three studies exploring the neurocognitive performance of adolescent athletes pre- and postinjury using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) battery. The first study examined the interaction effects of age, learning disability (LD), and previous concussion history on cognitive performance at a baseline in a sample of 1823 Finnish adolescent athletes. The second study explored the usefulness of on-field signs of concussion (i.e., LOC, amnesia, disorientation, postural instability, and vacant look) for predicting worse-than baseline neurocognitive performance during the acute, postinjury period in a sample of 34 concussed young athletes. The third study further examined the effects of on-field signs on the rate of acute neurocognitive decline in a sample of 32 concussed participants using reliable change indices (RCIs) derived from a healthy sample of 312 athletes.

Compared to typically developing athletes, athletes with LD had lower neurocognitive scores across all domains in a preseason baseline assessment. Additionally, athletes with LD demonstrated atypical maturational trajectories in verbal memory and visual motor speed. The number of prior concussions did not affect neurocognitive performance at the baseline. Hierarchical regression analyses were utilized to examine the predictive value of on-field signs for postinjury cognitive recovery. On-field LOC, amnesia and

vacant look were related to larger deficits in cognition at 7 days postinjury compared to concussed adolescent athletes without these signs. LOC accounted for 22% of the variance in verbal memory performance, and amnesia accounted for 15% of variance in verbal memory performance at group level. Vacant look sign accounted for 9% of the variance in visual memory scores. The effect of acute signs of concussion on postinjury cognitive functioning was further explored using RCI methodology. RCI methodology was applied to determine whether the change between baseline- and postinjury-cognitive functioning is meaningful at the individual level. The 1-year test-retest reliability of the Finnish version of ImPACT ranged from .39 to .71. RCIs derived from a healthy sample were calculated and applied to concussed sample. Athletes with an acute LOC, amnesia, or postural instability were approximately 8 times more likely to have impairments in two or more cognitive areas evaluated by ImPACT on day 3 postinjury. Acute on-field disorientation or a vacant look did not lead to reliable cognitive decline.

In all, the findings of the present study suggest that cognitive functioning develops throughout adolescence and that athletes with LD differ from their counterparts in cognitive maturational trajectories. Separate reference values for LD athletes are needed, considering their unique cognitive development. Baseline testing might be beneficial in subpopulations such as youth athletes and athletes with LD that display large variability in cognitive performance or differing developmental trajectories over time. Based on the present study, the presence of LOC, amnesia, or vacant look are risk factors for longer recovery times. The presence of acute postural instability might also indicate a more severe injury that warrants an intensive cognitive follow-up. The present findings have direct implications for concussion recognition, evaluation, and management. Reference values and reliable change indices for Finnish language and culture are provided for youth athletes and can be directly implemented in real-life situations. Overall, this study adds valuable information about the neurocognitive performance of youth athletes.

TIIVISTELMÄ

Aivotärähdys on yleinen vamma kovavauhtisissa urheilulajeissa, kuten jääkiekossa. Asianmukainen aivotärähdysten tunnistaminen, arviointi ja seuranta on tärkeää, jotta vältytään vaikeammilta vammoilta, mahdollisilta pitkäaikaisilta vaikutuksilta ja uran ennenaikaiselta päättymiseltä. Verrattuna aikuisiin nuoret ovat alttiimpia aivotärähdyksille. Nuoren aivotärähdys saattaa aiheuttaa vakavia akuutteja ja pitkäaikaisia vaikutuksia kehittyvälle urheilijalle. Aivotärähdyksen varhainen tunnistaminen ja arviointi tapahtuu välittömästi tapahtumapaikalla. Havaittavissa olevia aivotärähdyksen merkkejä ovat tajunnanmenetys, muistinmenetys, sekavuus, tasapainovaikeus ja tyhjä katse. Aivotärähdyksen arviointi tulisi suorittaa monipuolisesti eri toimintoja arvioiden. Vaikka neuropsykologinen arviointi ei yksin riitä, pidetään neuropsykologista tutkimusta aivotärähdysten arvioinnin kulmakivenä. Jotta voidaan tunnistaa vamman jälkeinen epätyypillinen aivotoiminta, on tärkeää tuottaa tietoa tyypillisestä kognitiivisesta suoriutumisesta ja kehityksestä sekä tuottaa viitearvoja kliiniseen käyttöön. Tämän tutkimuksen yleisenä tavoitteena on tutkia nuorten urheilijoiden kognitiivista suoriutumista ja vamman jälkeistä kognitiivista heikentymistä. Tutkimuksessa myös selvitetään, onko aivotärähdykseen viittaavilla merkeillä yhteyttä vamman jälkeiseen neurokognitiiviseen heikentymiseen. Lisäksi tutkimuksen tavoitteena on tutkia iän, aivotärähdyshistorian, oppimisvaikeuden ja toistotestauksen merkitystä aivotärähdysten arvioinnissa.

Väitöskirja sisältää kolme osatutkimusta, joissa tutkitaan nuorten urheilijoiden kognitiivista suoriutumista ennen ja jälkeen vamman käyttäen kognitiivista testipatteristoa: the Immediate Post-Concussion Assessment and Cognitive Testing battery (ImPACT). Ensimmäisessä tutkimuksessa tarkasteltiin iän, oppimisvaikeuden ja aivotärähdyshistorian yhteisvaikutusta kognitiiviseen suoriutumiseen 1823:n nuoren suomalaisen urheilijan lähtötaso aineistossa. Toisessa tutkimuksessa selvitettiin, voivatko aivotärähdyksen merkit (tajunnanmenetys, muistinmenetys, sekavuus, tasapainovaikeus ja tyhjä katse) ennustaa heikentynyttä kognitiivista suoriutumista viikko vamman jälkeen 34:n aivotärähdyksen saaneen nuoren urheilijan aineistossa. Kolmannessa osatyössä tutkittiin vielä syvällisemmin aivotärähdyksen merkkien vaikutusta akuuttiin luotettavaan kognitiiviseen heikentymiseen 32:n aivotärähdyksen saaneen nuoren aineistossa. Luotettava kognitiivinen muutos laskettiin terveiden urheilijoiden aineistosta (n=312) käyttäen Reliable change indices (RCI)- menetelmää.

Urheilijat, joilla oli oppimisvaikeuksia, saivat heikompia pisteitä kaikissa osa-alueissa ennen kauden alkua suoritetussa neurokognitiivisessa lähtötasotestissä verrattuna tyypillisesti kehittyviin nuoriin. Lisäksi urheilijat, joilla oli oppimisvaikeuksia, vaikuttivat kehittyvän epätyypillisesti

kielellisessä muistissa ja visuaalismotorisessa nopeudessa. Aiempien aivotärähdysten lukumäärä ei vaikuttanut urheilijoiden neurokognitiiviseen suoriutumiseen lähtötasolla. Aivotärähdyksen merkkien yhteyttä vamman jälkeiseen kognitiiviseen toipumiseen tutkittiin hierarkkisen regressioanalyysin avulla.

Jäällä havaittu tajunnanmenetys, muistinmenetys ja tyhjä katse olivat viikko vammasta arvioituna yhteydessä suurempaan kognitiiviseen heikentymiseen verrattuna aivotärähdyksen saaneisiin urheilijoihin, joilla ei ollut näitä merkkejä. Tajunnanmenetys selitti 22 % kielellisen muistisuoriutumisen vaihtelusta ja muistinmenetys selitti 15 % kielellisen muistisuoriutumisen vaihtelusta ryhmätasolla. Tyhjä katse puolestaan selitti 9 % aivotärähdyksen saaneen urheilijan näönvaraisen muistin vaihtelusta. Aivotärähdyksen merkkien vaikutusta vamman jälkeiseen kognitiiviseen suoriutumiseen tutkittiin edelleen käyttäen RCI-menetelmää. RCI-menetelmän avulla määriteltiin, millainen muutos vamman jälkeen kognitiossa vaadittiin, jotta sillä olisi merkitystä yksilölle ja kliinisessä työssä. Suomenkielisen ImPACT-menetelmän yhden vuoden toistomittaus reliabiliteetti osatesteille vaihteli .39 ja .71 välillä. Luotettavaa muutosta kuvaavat arvot (RCIs) laskettiin terveiden urheilijoiden aineistosta ja arvoja sovellettiin aivotärähdyksen saaneiden aineistoon. Akuutin tajunnanmenetyksen, muistinmenetyksen tai tasapainovaikeuden kokeneilla urheilijoilla, oli noin kahdeksankertainen todennäköisyys siihen, että heillä näkyi heikentymistä kahdessa tai useammassa kognition osa-alueessa 3 päivää vamman jälkeen. Urheilijan sekavuus tai tyhjä katse eivät puolestaan aiheuttaneet luotettavaa kognitiivista heikentymistä.

Kaiken kaikkiaan tutkimuksemme osoittaa, että nuoren kognitiivinen toiminta kehittyy läpi nuoruusvuosien ja urheilijat, joilla on oppimisvaikeuksia, eroavat vertaisistaan kognitiivisessa kehityskulussa. Urheilijoille, joilla on oppimisvaikeuksia, tarvitaan erilliset viitearvotiedot, jotta voidaan huomioida heidän ainutlaatuinen kognitiivinen kehityksensä. Lähtötasoarviointi saattaa olla hyödyllistä nuorilla ja oppimisvaikeuksia omaavilla urheilijoilla, sillä näissä alaryhmissä suurta vaihtelua lyhyessäkin ajassa kognitiivisissa taidoissa ja kehityksessä. Tämän tutkimuksen perusteella vamman yhteydessä ilmenevä tajunnanmenetys, muistinmenetys, tasapainovaikeus ja tyhjä katse saattavat viitata vakavampaan vammaan ja olla riskitekijöitä pitkittyneelle toipumiselle, minkä vuoksi tarvitaan kognitiivista seurantaa. Tämän tutkimuksen tuloksia voidaan suoraan hyödyntää suomalaisten jääkiekkoilijoiden aivotärähdysten tunnistamiseen, arviointiin ja seurantaan. Tarjoamme suomenkieliset nuorten viitearvotiedot ja luotettavaa muutosta kuvaavat arvot (RCIs), joita voidaan käyttää aidoissa tilanteissa ja kliinisessä työssä. Kokonaisuudessaan tutkimuksemme tuo lisää arvokasta tietoa nuorten urheilijoiden neurokognitiivisesta suoriutumisesta.

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original publications, referred to in the text by Roman numerals I-III.

I Peltonen, K., Vartiainen, M., Laitala-Leinonen, T., Koskinen, S., Luoto, T., Pertab, J., & Hokkanen, L. (2018). Adolescent athletes with learning disability display atypical maturational trajectories on concussion baseline testing: Implications based on a Finnish sample, *Child Neuropsychology*, 25(3), 336–351, DOI: 10.1080/09297049.2018.1474865

II Peltonen, K., Launes, J., Koskinen, S., Vartiainen, M., Pajunen, S., Pertab, J., Laitala, T. & Hokkanen, L. (2020). On-field signs of concussion predict deficits in cognitive functioning: loss of consciousness, amnesia and vacant look. *Translational Sports Medicine* 3(6), 565-573, DOI: 10.1002/tsm2.179

III Peltonen, K., Vartiainen, M., Koskinen, S., Pertab, J., Laitala, T. & Hokkanen, L. (2020). Post-Concussion Acute Signs and Reliable Cognitive Decline in a Finnish Youth Ice Hockey Sample. *Archives of Clinical Neuropsychology*, 2020 Nov 19: acaa108. Epub ahead of print. DOI: 10.1093/arclin/acaa108.

ABBREVIATIONS

AAN	The American Academy of Neurology
ACE	Acute Concussion Evaluation
ADD	Attention Deficit Disorder
ADHD	Attention Deficit Hyperactivity Disorder
ANAM	Automated Neurocognitive Assessment Metrics
ATTEX	The Attention and Executive Function Rating Inventory
BESS	Balance Error Scoring System testing
CIs	Confidence intervals
CVS	Concussion Vital Signs
FTN	Finger-to-nose task
GCS	Glascow Coma Scale
ICC	The Intraclass Correlation Coefficient
ImPACT	Immediate Post-Concussion Assessment and Cognitive Testing battery
K-D	The King-Devick
LD	Learning disability
LOC	Loss of consciousness
mTBI	Mild traumatic brain injury
NHL	National Hockey League
PCS	Post-Concussion Scale
PCSI	Postconcussion Symptom Inventory
PCSS	Post-Concussion Symptoms Score
PTA	Post traumatic amnesia
RCI	The reliable change index
SAC	Standardized Assessment of Concussion
SCAT	The Sport Concussion Assessment Tool
SCAT3	The Sport Assessment Tool - 3th edition
SCAT5	The Sport Assessment Tool - 5th edition
SRC	Sport-related concussion
TBI	Traumatic brain injury

1 INTRODUCTION

Injuries occur in high-velocity sports. Appropriate clinical identification, evaluation, and management of athletes with sport-related concussion (SRC) is crucial for increasing player safety and minimizing the risk for possible long-term deficits (Davis et al., 2017; Halstead, Walter & The Council on Sports Medicine and Fitness, 2010; McCrory et al., 2017). Effective concussion management is especially important when the injury occurs in the developing young athlete (Brown et al., 2014). Based on recent studies, young athletes may be more prone to concussions than adults, and because of the ongoing neurocognitive development throughout their adolescence, concussion may cause severe acute and long-term complications in developing athletes (Marar, McIlvain, Fields & Comstock, 2012; Patel, Shivdasani & Baker, 2005). This cognitive maturational process has direct implications for the evaluation and management of concussions in youth (Patel, Shivdasani & Baker, 2005). Several grading systems and return-to-play criteria are available following concussion. However, only a few of these are specifically applicable to children and adolescents (Patel, Shivdasani & Baker, 2005).

2 REVIEW OF THE LITERATURE

2.1 CONCUSSION IN SPORTS

Concussion in Sports Group (McCrory et al., 2017) has defined sport-related concussion (SRC) as a traumatic brain injury induced by biomechanical forces. Concussion is classified as a subset of mild traumatic brain injury (mTBI) on the less severe end of the brain injury spectrum (Harmon et al., 2013). Concussion may be caused by a direct blow to either the head, face, neck or elsewhere on the body. Sport-related concussion typically results in rapid onset of short-lived impairment of neurological function that resolves spontaneously. Sometimes signs and symptoms evolve over a number of minutes to hours. Concussion might lead to neuropathological changes, but the acute clinical signs and symptoms of concussion usually reflect a functional disturbance rather than a structural injury, which is why no abnormalities are normally seen on standard structural neuroimaging (Aivovammat: Käypä hoito -suositus, 2021; McCrory et al., 2017). Concussion signs may or may not involve loss of consciousness. The clinical signs and symptoms cannot be explained by drug, alcohol, or medication use, other injuries, or other comorbidities (McCrory et al., 2017).

The term concussion has been criticized for having neither a clear definition nor a pathological meaning (Sharp & Jetkins, 2015). Concussion is seen as a transient and benign injury that needs only a little medical attention and usually resolves spontaneously (Sharp & Jetkins, 2015). However, in some cases the symptoms of concussion may persist many years after the injury and may potentially cause long-term effects (Sariaslan et al., 2016). The severity of traumatic brain injuries is primarily classified using clinical evaluation, which is non-specific and has poor predictive value for long-term disability (Tenovuo et al., 2021). The early labels of injury severity determines how the patient is treated in the healthcare system at large (Tenovuo et al., 2021). The injury label has important clinical implications for the patient. Some clinicians suggest that the term concussion should be avoided and instead a unified classification of the severity of traumatic brain injury (TBI) should be used to avoid ambiguity (Sharp & Jetkins, 2015).

2.1.1 YOUNG DEVELOPING ATHLETE WITH CONCUSSION

Cognitive abilities develop with increasing age in adolescence. Many structural and functional changes occur in the brain during adolescence (Steinberg, 2005). Even relatively simple structural measures (e.g., the ratio of white-to-gray matter) demonstrate extensive changes into late adolescence (Giedd et al., 1999; Sowell et al., 2001; Sowell et al., 2002). Significant changes and growth have been reported in multiple regions of the prefrontal cortex throughout the teen-age years, especially due to myelination and pruning (Sowell, Delis, Stiles & Jernigan, 2001; Sowell et al., 2002). General intelligence has been reported as stable across development (Salthouse, 2004), yet several studies have reported improved performance from childhood to late adolescence in attention, executive functioning and working memory (Ang 2008, 2010; Gao et al., 2011; Klenberg, Korkman & Lahti-Nuuttila, 2001). Maturation during adolescence contributes to dramatic changes, especially in higher order cognitive abilities such as executive functioning, metacognition, self-evaluation, self-regulation and the coordination of affect and cognition (Steinberg, 2005).

The child's brain is developing rapidly during the early school-age years. Korkman and colleagues' (2001) study concerning children's normal neurocognitive development explored the effect of age across the range 5-to-12 years on attention and executive functioning, language, sensorimotor functions, visuospatial functions, and memory and learning. The effect of age in their study was very significant for all cognitive domains; however, the effect of age was more significant in the 5-8 age group than in the 9-12 year age group. The conclusion was that the neurocognitive development is rapid between ages 5-to-8 years and more moderate between the ages of 9-to-12 years (Korkman, Kemp & Kirk, 2001).

According to Piaget, the formal operational stage of cognitive development, with improved inductive and deductive reasoning skills, begins in early adolescence (ages 10-13) (Brown, Patel & Darmawan, 2017). Athletes show rapid improvements in reasoning, information processing and expertise during early adolescence (Steinberg, 2005). Athletes at this developmental stage may not fully comprehend the potential long-term consequences of brain injuries and, therefore, might fail to seek medical attention or to follow treatment recommendations (Patel et al., 2005). Parents and family have an important role in concussion management at this stage (Patel et al., 2005).

Abstract thinking and the ability to understand the consequences of behavior improves extensively during the middle adolescence (years 14-16) (Brown, Patel & Darmawan, 2017). Adolescents can observe their own behavior and analyze what was done correctly or what could be improved and correct their behavior according to their observations (Brown, Patel & Darmawan, 2017). A shift towards independency occurs at this stage. Adolescents are highly influenced by peers and media (Patel et al., 2005). There is a risk that an injured athlete at this developmental stage will continue to participate in sports despite recommendations against it (Patel et al., 2005). Participation in sports activities can be extremely important to athletes during middle adolescence, and an injury might be emotionally and socially difficult to cope with (Patel et al., 2005).

The understanding of interpersonal and social relationships matures in late adolescence (ages 17-19), and abstract thinking characterizes this stage of development (Patel et al., 2005). Athletes are more realistic about their abilities and goals in sport (Brown, Patel & Darmawan, 2017). Athletes in late adolescence are fully capable of competitive sports and specialization when their intellectual and functional capacity and abstract thinking are developed (Brown, Patel & Darmawan, 2017). Decision making is more future oriented in late adolescence. Other competing priorities, such as academics, career, or dating, may displace the importance of sports participation (Brown, Patel & Darmawan, 2017). Adolescents understand and take into consideration the acute and long-term consequences of brain-injuries (Patel et al., 2005). Young athletes' cognitive, psychosocial, and physical developmental stage should always be taken into consideration in the management and assessment of concussion.

2.1.2 INCIDENCE OF SPORT-RELATED CONCUSSION

Sport-related concussion is a common injury in high-velocity sports such as ice hockey, rugby, and American football. The risk of concussion is higher in ice hockey than in many other sports. The injury rate of concussions documented in men's ice hockey is 1.4/1000 player games in the World Championships over a 7-year period (Tuominen, Stuart, Aubry, Kannus & Parkkari, 2015). It is estimated that 2.5 concussions occur for every 10,000 athletic exposures for high school athletes involved in all sports, and an athletic exposure is defined as one game or training session the athlete participates in (Guerriero, Proctor, Mannix & Meehan, 2012). Kontos and colleagues (2016) studied the incidence of concussion among competition-level youth ice hockey players (ages 12-18 years). Their study reported a combined incidence rate for games and practices of 1.58 concussions per 1000 athletic exposures (Kontos et al., 2016). The incidence rate of concussion for practices and games in the 12-to-14-year-old age group was 2.84/1000 athletic exposures; it was 1.18/1000 exposures in the 15-to-18-year-old age group (Kontos et al., 2016). The study showed that younger players had a 2.4 times higher injury rate than older players. One reason for increased risk for concussion in early adolescence may be the disparity in size, strength, and speed across athletes at this developmental stage and the introduction of checking at age 13 (Kontos et al., 2016). The concussion rate increases in youth ice hockey around age 13 when checking becomes permitted in the game (Hutchison, Comper, Meeuwisse & Echemendia, 2015b; Johnson, 2011; Macpherson, Rothman & Howard, 2006). The majority of concussions are caused by bodychecking at all levels of play (Johnson, 2011). A common cause for concussion is a check to the head (Tuominen et al., 2015).

Playing position in ice hockey has been associated with the risk of concussion (Hutchison, Comper, Meeuwisse & Echemendia, 2015a). A study concerning adult National Hockey League (NHL) players suggests that the injury risk is higher for forwards than for defensemen (Hutchison, Comper, Meeuwisse & Echemendia, 2015a). The same study reported that 88% of diagnosed concussions involved contact with an opponent. The majority of concussions occurred in the perimeter (53 %), around 47% of the concussions occurred in open ice and 45% occurred in the defensive zone (Hutchison et al., 2015a). An athlete's time on ice per game (higher than average), in addition to the playing position, is also associated with a higher concussion risk (Stevens, Lassonde, de Beaumont & Keenan, 2008). An NHL study by Bruce and colleagues (2018) showed that being in a fight, having a hit from another player's shoulder and having a secondary hit on the ice were all risk factors associated with concussion.

2.1.3 RECOGNITION AND SIGNS OF CONCUSSION

The initial recognition and evaluation of concussion takes place acutely on-ice by the healthcare professionals or the team's first aid personnel. The so-called "red flags" that require immediate removal from play and calling an ambulance are neck pain or tenderness, double vision, weakness or tingling/burning in arms or legs, severe or increasing headache, seizure or convulsion, loss of consciousness, deteriorating conscious state, vomiting, increasing restlessness, agitation, or combativeness (Echemendia et al., 2017).

There are some important issues to consider when concussion occurs to a child. The child's skull is relatively thin with poorly developed cervical musculature supporting the school-aged child's head (Davis & Purcell, 2014). The same impact force can result in a more severe injury to a child's brain than to an adult's due to structural differences (Davis & Purcell, 2014). Children are physically, cognitively, and emotionally very different from adults; thus, concussion in children must be evaluated and managed with caution.

Researchers have recently focused on identifying observable signs of concussion. Visible signs of concussion such as on-ice loss of consciousness, postural instability and vacant look have been found to indicate a concussion diagnosis in studies using video analysis (Echemendia et al, 2018; Gardner, Howell, Levi & Iverson, 2017b; Gardner, Levi & Iverson, 2017c). Commonly acknowledged initial signs of concussion include loss of consciousness (LOC), amnesia, disorientation, postural instability, and vacant look (McCrory et al., 2013). The frequency with which they occur varies, however. Previous studies of American football, Australian football, rugby, ice hockey, basketball and soccer have found the following incidences of on-field signs of concussion: LOC in approximately 5-10% (Harmon et al., 2013; McCrea, Broglio &

McAllister, 2020), amnesia in 15-25% McCrea, Broglio & McAllister, 2020; Guskiewicz et al., 2003; Guskiewicz, Weaver, Padua & Garrett, 2000), disorientation in 44-48% (Guskiewicz et al., 2000; Lovell et al., 2003), postural instability in 20-60% (Guskiewicz et al., 2000; Davis & Makdissi, 2016; Gardner, Kohler, Levi & Iverson, 2017a; Gardner, Howell & Iverson, 2018) and vacant look in 75% of acute cases (Gardner et al., 2017a).

2.1.4 CLINICAL OUTCOME AND PREDICTORS OF SHORT-TERM RECOVERY

The clinical outcome of concussion varies individually. A wide variety of concussion symptoms exist (Table 1). Most of the symptoms are not specific to concussions but may also occur in other conditions. Postinjury symptoms are divided into four clinical domains: physical (headache, nausea etc.), cognitive (memory problems, difficult to concentrate etc.), emotional (irritable, sadness etc.) and sleep (drowsiness etc.) (Harmon et al., 2013). Headache, the most common symptom related to concussion, occurs in approximately 65-93% of cases, followed by fatigue (in 55-82%), dizziness (in 32-75%), and slowed mentation (in 44-60% of cases) (Rose, Weber, Collen & Heyer, 2015). Some postinjury symptoms overlap with other conditions, such as mood disorders, attention deficit disorder or sleep disturbance; therefore, it is important to clarify whether these symptoms existed prior to the injury (Harmon et al., 2013). Whiplash and concussion also share many similar post-injury symptoms; therefore, these two injuries may easily be confused (Gil & Decq, 2021). Several postinjury clinical factors have been associated with a worse outcome after concussion (Iverson et al., 2017): the severity of cognitive deficits, the development of post-traumatic headaches or migraines, dizziness, difficulties with oculomotor functioning and symptoms of depression (Iverson et al., 2017).

Table 1 *Symptoms of concussion (Harmon et al., 2013).*

Physical	Cognitive	Emotional	Sleep
Headache	Feeling mentally “foggy”	Irritable	Drowsiness
Nausea	Feeling slowed down	Sadness	Sleeping more than usual
Vomiting	Difficulty concentrating	More emotional	Sleeping less than usual
Balance problems	Difficulty remembering	Nervousness	Difficulty falling asleep
Dizziness	Forgetful of recent information/conversations		
Visual problems	Confused about recent events		
Fatigue	Answers questions slowly		
Sensitivity to light	Repeats questions		
Sensitivity to noise			
Numbness/tingling			
Dazed			
Stunned			

Large postinjury effects of concussion on neurocognitive functioning are usually found within 24 hours of injury; they reduce to moderate to small within days to weeks (Dougan, Horswill & Geffen, 2013). A meta-analysis showed large cognitive deficits in global functioning, memory acquisition and delayed memory within the first 24 hours postinjury (Belanger & Vanderploeg, 2005). However, these acute effects of concussion were diminished at 7-10 days postinjury (Belanger & Vanderploeg, 2005).

Postinjury neurocognitive deficits vary depending on the severity of the brain injury. The most common cognitive postinjury deficits are the same in adults and children, namely reduced information processing speed, poor attention, and impaired executive functioning (McCrory, Collie, Anderson & Davis, 2004). Cognitive impairments in mTBI are typically detected in processing speed, attention and working memory (Meares et al., 2008). However, the most common cognitive deficits in moderate-to-severe TBIs are problems with attention and executive functioning, memory and learning problems, problems with communication and overall slowness of thinking and functioning (Nybo, 2005). Concussion symptoms resolve approximately in 7-10 days, but some athletes suffer persistent symptoms and prolonged recovery, which is defined as still being symptomatic 2 weeks after injury or after four weeks in the case of children (McCrory et al., 2017). The cognitive deficits usually resolve in three months in mild brain injuries (Echemendia, Putukian, Macklin, Julian, & Shoss, 2001). Cognitive deficits tend to improve most during the first 6-12 months postinjury in moderate to severe TBI; however, the recovery decelerates after the first year and might plateau by 2 years (Schretlen & Shapiro, 2003).

Numerous grading systems have been published that estimate the severity of concussion based on clinical signs and symptoms (Patel, Shivdasani & Baker, 2005). They have traditionally been based on the presence or absence and/or duration of loss of consciousness, amnesia, and confusion (Report of the quality standards subcommittee 1997; Cantu 1986; Kelly et al., 1991; Roberts 1992). Injury characteristics such as LOC and amnesia have been chosen because studies have reported an association between them and worse clinical outcomes (Merritt, Rabinowitz & Arnett, 2015; Dougan, Horswill & Geffen, 2014). There is also evidence that the severity and outcome following a moderate-to-severe traumatic brain injury may correlate with the duration of LOC or posttraumatic amnesia (PTA) (Patel et al., 2005), but such an association has not been clearly proven in mild traumatic brain injuries (Patel et al., 2005).

Two of the most traditional concussion grading systems are the Cantu and the American Academy of Neurology (AAN) guidelines (Thomas et al., 2011). The 1986 published Cantu grading system used both the duration of loss of consciousness (LOC) and posttraumatic amnesia to grade the injury (Cantu 1986). Grade 1 was classified as a mild concussion with no LOC and the posttraumatic amnesia (PTA) persisting less than 30 minutes. Grade 2 was a moderate concussion with less than 5 minutes LOC or more than 30 minutes of posttraumatic amnesia. Grade 3 was classified as a severe concussion with 5 or more minutes of LOC or 24 or more hours of posttraumatic amnesia. It was unclear in this grading system how to grade a player with a concussion without LOC and PTA but with prolonged postconcussion symptoms such as headache or balance problems (Thomas et al., 2011). The AAN published a concussion guideline in 1997 in which both duration of LOC and posttraumatic amnesia were still given a high priority, while confusion and any disturbance of neural function were added in the grading system (Report of the quality standards subcommittee 1997). The Cantu and AAN grading system differed in their targeted emphasis on LOC or PTA. These two markers of concussion may be important in a prognosis of severe brain injury cases, but their usefulness in prognosis of milder cases has been under debate. Concussion grading scales for severity are no longer recommended because they poorly predict the clinical outcome (Giza at el., 2013; McCrory et al., 2009). Other on-field signs and symptoms, such as on-field dizziness, migraine headache symptoms and self-reported cognitive decline, have recently been studied as potential predictors of clinical outcome and recovery (Lau, Lovell, Collins & Pardini, 2009; Lau, Kontos, Collins, Mucha & Lovell, 2011).

2.2 EVALUATION OF CONCUSSION

The multifaceted assessment approach integrates outcome measures across multiple domains of functioning (Echemendia et al., 2013). This approach recommends neuropsychological assessment, balance testing and evaluation of symptoms (McCrory et al., 2017). The importance of an evaluation of oculomotor and vestibular functioning has also been recognized recently (Kontos et al., 2016). The assessment process should take other aspects that might affect the outcome into consideration, such as concussion history and comorbidities or complicating factors (Echemendia et al., 2013).

The concussion evaluation process begins acutely on the field or ice. Recognition of concussion can be challenging, because many athletes do not have any visible signs of concussion or do not report any symptoms. Upon arrival on the ice, the clinician should perform a primary survey, including evaluation of the athlete’s airway, breathing, and circulation (Littleton & Guskiewicz, 2013). All life-threatening conditions, such as cervical spine injuries and cranial fractures, should also be ruled out before removing the athlete from the ice (Littleton & Guskiewicz, 2013). The sideline evaluation can occur if all serious and life-threatening conditions are ruled out.

2.2.1 SIDELINE EVALUATION

The Sport Concussion Assessment Tool (SCAT; now in its 5th edition SCAT5) is the most widely used sideline evaluation method designed to assess acute effects of concussion. The SCAT is designed to capture the clinical signs and symptoms, cognitive deficits and neurological impairments that often occur after concussion (Echemendia et al., 2017). On-ice evaluation of concussion include assessing observable acute signs (loss of consciousness, amnesia, disorientation, postural instability and vacant look), the state of an athlete's consciousness (Glascow Coma Scale; GCS) and orientation (Maddocks Score). Sideline assessment includes symptom evaluation (Symptoms Scale), cognitive evaluation (Standardized Assessment of Concussion; SAC), balance examination (Modified Balance Error Scoring System testing; BESS and Tandem Gait) and coordination examination (Finger-to-nose task; FTN) (Guskiewicz et al., 2013).

2.2.2 POST-INJURY SELF-REPORTED SYMPTOMS

Symptoms scales are used to evaluate acute symptoms and to track the recovery. The most utilized symptoms scale is the Post-Concussion Scale (PCS) (Lovell et al., 2006). The post-concussion scale (revised) was the first published scale used widely in research. The post-concussion scale includes the most common symptoms following concussion. The athlete self-assesses the presence of these symptoms and their severity with a 7-point Likert scale. The scale was included in the computerized neurocognitive test battery ImPACT in 2000 (Alla, Sullivan, Hale & McCrory, 2009). The ImPACT incorporated the PCS with 21 items at first, but later the symptom “visual problems” was added, making it a 22-item scale (Lovell et al., 2006). Another widely used symptoms scale is the Post-Concussion Symptoms Score (PCSS) that is incorporated into the SCAT3 (Guskiewicz et al., 2013). PCSS has 22 items and uses a 7-point Likert scale rating to assess both the presence of symptoms and their severity (Guskiewicz et al., 2013). Table 2. presents a comparison of the symptoms in the PCS and the PCSS, both of which can be used with adults and adolescents.

Other measures have been developed for younger children. The Child-SCAT3 (2013) is a concussion assessment tool aimed at children aged 5 to 12 years. The Child-SCAT3 includes various components that evaluate the number (0-20) and severity of symptoms, as assessed by the child and by the parent (Brooks, Snedden, Mixis, Hetzel & McGuine, 2017). Other symptom scales have also been used with children, such as the Postconcussion Symptom Inventory (PCSI) (Sady, Vaughan & Gioia, 2014), the Acute Concussion Evaluation (ACE) (Gioia, Collins & Isquith, 2008), and the Rivermead Postconcussion Symptoms Questionnaire (Echemendia et al., 2013; King et al., 1995). These symptoms scales are modified to fit children’s cognitive level and, for example, the presence or absence of symptoms are clarified by an interview (Gioia, Collins & Isquith, 2008; Sady, Vaughan & Gioia, 2014).

Table 2 *Symptoms in the Post-Concussion Scale (Lovell et al., 2006) and in the Post-Concussion Symptoms Score (Guskiewicz et al., 2013).*

Post-Concussion Scale		Post-Concussion Symptoms Score
1.	Headache	Headache
2.	Fatigue	Fatigue or low energy
3.	Feeling slowed down	Feeling slowed down
4.	Drowsiness	Drowsiness
5.	Difficulty concentrating	Difficulty concentrating
6.	Feeling mentally “foggy”	Feeling like “in a fog“
7.	Dizziness	Dizziness
8.	Difficulty remembering	Difficulty remembering
9.	Sensitivity to light	Sensitivity to light
10.	Balance problems	Balance problems
11.	Sensitivity to noise	Sensitivity to noise
12.	Irritability	Irritability
13.	Trouble falling asleep	Trouble falling asleep
14.	Visual problems	Blurred vision
15.	Nervousness	Nervous or Anxious
16.	Feeling more emotional	More emotional
17.	Sadness	Sadness
18.	Nausea	Nausea or vomiting
19.	Vomiting	
20.	Sleeping more than usual	
21.	Sleeping less than usual	
22.	Numbness or tingling	
		“Pressure in head”
		“Don’t feel right”
		Confusion
		Neck Pain

2.2.3 BASELINE ASSESSMENT

Many organizations have adopted preseason baseline testing for their athletes. The preinjury baseline in the case of concussion is compared to postinjury test results to determine whether cognitive deficits exist. Baseline testing is thought to increase the diagnostic accuracy by taking into account the variability between individuals in preinjury cognitive functioning (Echemendia et al., 2013). However, baseline testing is expensive and time consuming. There is also little empirical support for the necessity of baseline assessment despite its common use (Randolph & Kirkwood, 2009).

Echemendia and colleagues (2012) examined the utility of baseline testing among 266 concussed athletes using the ImPACT test battery at baseline and postinjury. They compared the baseline method and the normative data comparison method and concluded that clinically meaningful cognitive decline can be detected without baseline data as long as well-developed normative data exists (Echemendia et al., 2012). The use of baseline testing might be beneficial in subpopulations with conditions known to affect cognition, such as Attention Deficit Hyperactivity Disorder (ADHD) or Attention Deficit Disorder (ADD), learning disability (LD) or athletes with a concussion history (Collins et al., 1999; Kontos et al., 2016). Athletes with cognitive abilities clearly higher or lower than average can also benefit from the use of baseline data (Echemendia et al., 2013).

There is a rapid change in cognitive functioning during childhood and throughout adolescence due to the normal neurological maturation process (McCrory, Collie, Anderson & Davis, 2004; Patel et al., 2005). The return to the athlete's own neurocognitive baseline is considered to indicate a resolution of effects of the concussion in adults. The return to the baseline profile measured a long time ago in young athletes does not necessarily indicate a resolution of effects of concussion, because cognitive improvement with time is expected (Patel et al., 2005). The possible effect on cognitive development should always be taken into consideration when interpreting the results of neuropsychological assessment (Patel et al., 2005). Therefore, annual baseline testing is recommended in guidelines for young athletes with maturing cognitive skills (Broglio et al., 2014).

2.2.4 NEUROCOGNITIVE ASSESSMENT APPROACHES

The Concussion in Sports group has defined neuropsychological assessment as the "cornerstone" of concussion management (McCrory et al., 2013). It is not useful alone, however, and the importance of the multimodal approach in concussion evaluation involving symptom reporting, vestibular, oculomotor and balance testing and cognitive assessment has been emphasized (McCrory et al., 2017). Rapid serial evaluations during the first days and weeks postinjury are necessary for return-to-play decisions, and cognitive assessment methods have been developed with this purpose in mind. Concussion-focused protocols, including paper and pencil neuropsychological evaluation, were introduced for professional and collegiate athletes in the late 1980s (Kontos, Sufrinko, Womble & Kegel, 2016b). Traditional paper and pencil assessment methods are reasonably reliable, valid and sensitive to the effects of concussion (Echemendia et al., 2013). Paper and pencil tests can be selected to fit both the specific needs of the individual and the domains of neuropsychological importance (Echemendia et al., 2013). However, paper and pencil assessments are time consuming and might be affected by the test administrator and scoring variability (Iverson & Schatz, 2014). There are also a limited number of neuropsychologists available to perform the paper and pencil assessment at the acute phase following a concussion.

Computerized test batteries, developed in the 1990s to provide an alternative to traditional paper and pencil tests, are now widely utilized in sports settings (Kontos et al., 2016b). Many computerized tests are available, such as the Automated Neurocognitive Assessment Metrics (ANAM), the Axon Sports Computerized Cognitive Assessment Tool, Concussion Vital Signs (CVS) and the HeadMinder CRI, but the most studied and utilized is the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT®) battery. Computerized neurocognitive tests usually include cognitive domains such as memory, reaction time, processing speed, and attention (Kontos et al., 2016b).

Adolescent athletes can usually be assessed with the same evaluation methods as adults. However, in the case of children, not only their cognitive, physical, and emotional development but also their capacity to self-evaluate symptoms should be taken into consideration (Echemendia et al., 2013). There are only a few computerized neurocognitive test batteries used in children's sport concussion assessments (Echemendia et al., 2013). One of these methods is the Pediatric ImPACT, which is aimed at children aged from 5 to 12 (Gioia, Vaughan & Isquith, 2012).

There are several advantages to using computerized test batteries compared to traditional pen and pencil tests, for example, their brevity, ease of administration to large groups, and suitability for serial testing (Kontos et al., 2016). They can also be administered without a neuropsychologist present, although the expertise of a neuropsychologist in interpreting the results and making the decisions is needed (Echemendia et al., 2013). Computerized test batteries can also measure speed-related domains such as reaction time or processing speed more accurately than would be possible by an examiner with a stopwatch. Computerized test batteries have still been criticized for their psychometric properties, reliability and validity (Alsalaheen, Stockdale, Pechumer & Broglio, 2016; Broglio, Ferrara, Macciocchi, Baumgartner & Elliott, 2007; Nelson et al., 2016b).

Most of the computerized assessment methods are designed merely for screening and are limited in their contents. Brief cognitive testing tools are not a substitute for formal neuropsychological assessment (Echemendia et al., 2013). The comprehensive neuropsychological assessment is warranted in the case of a more serious head injury or persistent concussion symptoms. Some clinicians have adopted a hybrid approach because a formal neuropsychological assessment might be too time consuming and computerized test batteries too brief to assess all the domains affected by concussion (Echemendia et al., 2013). The hybrid approach is developed to maximize the advantages and minimize the weaknesses of the traditional and computerized approaches (Echemendia et al., 2020; Maerlender et al., 2010). One possibility of the hybrid approach is to use computerized test batteries at the baseline and both computerized and traditional tests postinjury

(Echemendia et al., 2013). There is no consensus among experts about which of the testing approaches—computerized testing, traditional neuropsychological testing, or a hybrid approach— is the best one in different situations.

2.2.5 COMPREHENSIVE NEUROPSYCHOLOGICAL ASSESSMENT

A comprehensive neuropsychological assessment may be needed in the case of a more severe injury or prolonged symptoms. The neuropsychological evaluation of athletes with TBI requires a multifaceted approach to assess different cognitive domains, psychiatric symptoms, psychological factors, and psychosocial functioning (Podell, Gifford, Boukagov & Goldberg 2010). Neuropsychological evaluation is crucial for measuring cognitive and emotional dysfunction following injury. Clinical neuropsychology is an important component of diagnosing, detecting recovery and developing treatment programs or planning therapy for TBI (Podell, Gifford, Boukagov & Goldberg 2010).

Formal neuropsychological assessment includes a wide variety of areas to be evaluated, such as the preinjury abilities, test engagement, neuropsychological domains and psychiatric or emotional status (Podell et al., 2010). The evaluated neuropsychological domains following a TBI are typically language and speech, visuospatial and construction, attention, executive functioning, memory, visuomotor and motor processes and personality and mood (Podell et al., 2010). Traditional tests have large normative databases and have been used over a long time period time in clinical settings (Echemendia et al., 2013). Paper and pencil tests require a face-to-face meeting, allowing easier behavioral observations of effort and testing approaches (Kontos, Sufrinko, Womble &Kegel, 2016). A face-to-face meeting also enables the assessment of auditory processing and nonvisual performance (Kontos et al., 2016).

2.3 MODIFYING FACTORS

2.3.1 LEARNING EFFECT AND THE RELIABLE CHANGE INDEX

Repeated cognitive assessment has become one of the primary objective tools in concussion management, even if there are learning effects involved (McCrory et al., 2013). An athlete might score better when a test is repeated in a short period of time because they have learned the items, or they have learned how to take the test (Grady, 2010). Test improvement in this case does not correspond to neurocognitive improvement, a phenomenon called the learning effect (Grady, 2010). Most of the computerized assessment methods provide parallel alternative tasks to try to minimize the potential learning effect. Computerized neurocognitive test batteries have become popular since their development in the 1990s for administering baseline testing (Kontos et al., 2016).

An advanced statistical methodology can also be used to compare pre- and postinjury performance to balance the effects of repeated testing (Iverson, Lovell & Collins, 2003). The reliable change index (RCI), a metric developed by Jacobson and Truax (1991), is designed to assess whether the change between repeated measurements is meaningful at an individual level. The RCI provides a confidence interval used to calculate whether a change in scores is statistically significant, considering the measurement error surrounding test-retest difference scores. T-tests and analysis of variance are common statistical methods in the human sciences, which are based on analyzing differences in group means (Zahra & Hedge, 2010). These statistical approaches are helpful in describing overall trends, but they are of limited use in understanding individual differences associated with concussion (Parsons, Notebaert, Shields & Guskiewicz, 2009). The RCI methodology is especially useful in small clinical samples (Zahra & Hedge, 2010).

2.3.2 UNDERLYING LEARNING DISABILITY AND ATTENTION DEFICIT HYPERACTIVITY DISORDER

LD is defined as a heterogeneous group of disorders consisting of difficulties in the acquisition and use of listening, speaking, reading, writing, and reasoning, or mathematical abilities and which is traditionally diagnosed in early childhood (DSM-5; American psychiatric Association, 2013). Approximately 5-15% of the population has developmental LD (American Psychiatric Association, 2013). Another common developmental disorder is attention deficit hyperactivity disorder (ADHD). According to DSM-V, ADHD is characterized by impairing and pervasive symptoms of inattention and/or hyperactivity impulsivity (American Psychiatric Association, 2013). The worldwide prevalence of ADHD is estimated to be approximately 5% of the population (Polanczyk, Silva de Lima, Horta, Biederman & Rohde, 2007).

Developmental disorders (LD and ADHD) share many common features with concussion, such as memory problems and attention deficits, which makes diagnosing and managing concussion challenging in these subgroups (Harmon et al., 2013). Athletes with LD or ADHD have performed worse than average in baseline cognitive testing (Nelson et al., 2016). Athletes with LD or ADHD also report more symptoms at baseline than people without these disorders (Iverson et al., 2015; Iverson et al., 2017). Using general normative data for these subgroups could potentially mislead practitioners to overestimate the severity and effects of concussion (Nelson et al., 2016). Therefore, separate normative data have been provided for these subgroups in the English language (Elbin, Kontos, Kegel, Johnson, Burkhart & Schatz, 2013;

Zuckerman, Lee, Odom, Solomon & Sills, 2013). The presence or absence of LD or ADHD is important when considering the relevance of postinjury test scores.

Some studies show that developmental disorders could confer increased risk for concussion (Nelson et al., 2016). Adolescents with LD or ADHD are at increased risk for numerous injuries and accidents, and most injuries happen in sporting activities (Brook & Boaz, 2006). There are studies indicating that self-reported concussions at baseline are more prevalent in athletes with LD or ADHD (Collins et al., 1999; Nelson et al., 2016). A sample of high school and collegiate athletes showed that the individuals with LD or ADHD were 2-3 times more likely to have experienced 3 or more concussions compared to their counterparts (Nelson et al., 2016). Athletes with a history of previous concussions are also at risk for future concussions (Abrahams et al., 2014), meaning that athletes with developmental disorders might be at increased risk for the cumulative effects of concussion.

There are studies exploring the association between LD or ADHD and clinical outcomes. A study showed a correlation between underlying ADHD and prolonged recovery from concussion (Miller et al., 2016). There is also a study showing a correlation between underlying LD and prolonged post-concussion symptoms (Zemek et al., 2016). However, Iverson et al. (2017) addressed this issue in a systematic review and concluded that most studies do not support the association between LD or ADHD and worse clinical outcomes. Cook and colleagues (2020) also concluded in their systematic review that no clear correlation exists between ADHD and worse clinical outcomes after a concussion. More careful planning and intervention regarding a return to school is still recommended for athletes with LD or ADHD (Iverson et al., 2017).

2.3.3 CONCUSSION HISTORY

There is a large body of research examining the effect of a previous concussion on neurocognitive performance across the lifespan. Some studies report that multiple concussions do not affect neurocognitive functioning (Broglio, Ferrara, Piland, & Anderson, 2006; Brooks et al., 2013; Iverson, Brooks, Lovell, & Collins, 2006), while others report that athletes with a history of multiple concussion have lower cognitive test scores and lingering post-concussive symptoms in preseason baseline testing (Elbin et al., 2012; Iverson, Echemedia, LaMarre, Brooks, & Gaetz, 2012; Iverson, Gaetz, Lovell & Collins, 2004; Nelson et al., 2016a; Schneider, Emery, Kang, Schneider, & Meeuwisse, 2010). Alsalaheen and colleagues (2017) examined the cumulative effects of concussion history on neurocognitive performance using ImPACT test battery at baseline in a systematic review. They found a declined visual memory in participants with one concussion, but otherwise there were no difference in baseline neurocognitive performance between those with and those without a history of concussions (Alsalaheen et al., 2017). It is still unclear whether the number of previous concussions should be used as an adjusting factor when interpreting the postinjury test results.

A study by Ellis and colleagues (2018) explored the effect of concussion history on symptoms burden and recovery following sport-related concussion in 7-19-year-old pediatric patients. They discovered that patients with prior concussions reported significantly more symptoms at initial postinjury assessment than those without previous concussions (Ellis, Krisko, Selci & Russell, 2018). Concussion history is associated with a risk for more severe or with a longer duration of symptoms and postinjury cognitive deficits (Giza et al., 2013). Subacute problems with headaches and preinjury mental health problems also appear to be risk factors for persistent postinjury symptoms (Iverson et al., 2017). An old recommendation suggested that an athlete should be suspended at least for the remaining season (or retire) if the athlete sustained 3 concussions (Thorndike, 1952). More recently, the boundary of 3 concussions has been questioned; instead, it has been suggested that there are no set number of concussions after which an athlete should retire, but the decision should be made individually (McCrory 2002).

2.3.4 CULTURAL AND LINGUISTIC BACKGROUND

There has been a growing interest in neuropsychology towards the effect of culture on neuropsychological performance among various cultural groups. Studies have focused on norm-related issues regarding cross-cultural neurocognitive assessment, translations, and cross-cultural differences in test performance (Echemendia et al., 2020; Vartiainen et al., 2019). There are also cross-cultural differences in educational and socioeconomic backgrounds and in experience with formal neurocognitive testing (Echemendia et al., 2020). Based on the research, we know that there are no culturally universal verbal or visual neuropsychological measures (Roselli & Ardila, 2003). Neuropsychological performance has been shown to vary depending on an athlete's culture, language of origin and educational level (Echemendia et al., 2020; Jones et al., 2014).

Performance speed is highly valued in many neuropsychological tasks. Mulenga and colleagues (2001) compared the neuropsychological performance of Zambian children to US norms, and they discovered that even if the participants were advised to perform the task as fast as possible, most Zambian children tended to work slowly. Other studies have noted the same phenomenon: Individuals from the US have been slightly faster than members of other cultures in speed of performance (Agranovich et al., 2011; Echemendia et al., 2020). Fast performance is obviously an important cultural value in the US but might not be in many other cultural groups (Rosselli & Ardila, 2003). Better performance is usually observed in the cultural group that has developed the test (Ardila, 1995). That is because the test usually reflects culturally relevant and existing neuropsychological skills, such as writing as a relevant motor skill in many western cultures and fishing as a relevant motor skill for Amazonian Indians (Ardila, 1995). Observed cross-cultural differences in cognitive performance might be due to a cultural effect rather than to a difference in cognitive abilities per se (Echemendia et al., 2020; Roivainen, 2010).

The ImPACT test was originally developed in the US, and there are multiple studies concerning the reliability, validity and other psychometric properties of the English-language version of ImPACT® (Maerlander et al., 2006; Schatz, Pardini, Lovell, Collins & Podell 2006; Schatz & Sandel 2013). There are multiple language versions of ImPACT available, but only a few studies assess the appropriateness of these translations and the cultural correspondence or validity of each test version. Ott and colleagues (2014) studied the difference on ImPACT baseline test performance in three different groups: Hispanic Spanish-speaking athletes completing the test in Spanish (n=2 087), Spanish-speaking athletes completing the test in English (n=9 733) and English-speaking athletes completing the test in English (n=11 955). They discovered that Spanish-speaking athletes completing the test in Spanish performed more poorly on all domains than athletes completing the test in English (Ott, Schatz, Solomon & Ryan, 2014). They concluded that there is a need for caution in interpreting ImPACT test results for Hispanic Americans. Similar differences in the ImPACT speed-related measures have been observed in Finnish adult athletes compared to English- or Czech-speaking samples (Vartiainen et al., 2019). More research is needed to address these cultural and linguistic issues on neurocognitive evaluation and methods used.

3 AIMS OF THE STUDY

This study's general aim was to enhance knowledge about young athletes' neurocognitive performance and postinjury cognitive deficits. Its objective was to assess athletes' neurocognitive performance in both a healthy and a concussed sample and to evaluate the relation between on-field signs of concussion and postinjury neurocognitive deficits. An additional aim was to assess the modifying factors in concussion assessment, such as age, concussion history, learning disability and repeated testing. The athletes were recruited from the Finnish ice hockey league.

I. Study I's aim was to explore the interaction effects of age, learning disability (LD), and previous concussion history on preseason baseline cognitive performance in a large sample of adolescent Finnish athletes. The hypothesis was that the number of concussions together with the LD would cumulatively impair neurocognitive performance at the baseline and that LD would cause an atypical developmental trajectory in at least some of the cognitive domains.

II. Study II's aim was to explore the usefulness of on-field signs of concussion (i.e., loss of consciousness (LOC), amnesia, disorientation, postural instability, and vacant look) for predicting worse-than-baseline neurocognitive performance during the acute postinjury period in the adolescents.

III. Study III's aim was to further examine the effects of the on-field signs of concussion on the rate of acute neurocognitive decline using reliable change indices (RCI) derived from a healthy control group of adolescent Finnish athletes.

4 METHODS

4.1 SUBJECTS

The data were collected as part of the University of Helsinki *Heads in the Game* project supported by the Ministry of Social Affairs and Health Finland (grant number 201510103). The Finnish Ice Hockey Association adopted a policy of encouraging baseline testing for all representative junior team athletes as part of their concussion management initiative, and this was performed as part of the project. Altogether 17 ice hockey clubs with elite-level junior hockey teams (age levels A, B and C) were recruited to the *Heads in the Game* project during the 2015- 2016 and 2016-2017 playing seasons. All 17 clubs in the Men's Finnish National Hockey League participated in the study. These clubs had multiple elite-level junior teams all across Finland (Figure 1). The project included preseason baseline assessments and a structured program to identify concussion and monitor recovery during the season. Advocacy and information leaflets were prepared and distributed, and training events were arranged for all the clubs' personnel during the baseline assessment week at all locations around Finland.

Figure 1 Approximal locations of seventeen ice hockey clubs that participated Heads in the game -project during 2015-2017 in fifteen cities. The clubs in systematic concussion follow-up are marked with an ellipse.

Four ice hockey clubs in Southern Finland were selected for a systematic follow up of concussions. These clubs were selected based on their close proximity to the University of Helsinki facilities where the postconcussion follow-up assessments occurred at days 3, 7, 14 and 30 (Figure 2). Other clubs received phone consultations when necessary. The clubs on the west coast were monitored separately in a project by Adjunct Professor Tiina Laitala from the University of Turku.

The primary identification and management of concussions were conducted by the clubs' medical personnel, who reported the injuries to the *Heads in the Game* contact person. The athletes participated in the project follow-ups until recovery. A full neuropsychological assessment was recommended and arranged for athletes with prolonged symptoms. The project was approved by the Ethical Committee of the Helsinki Uusimaa Hospital District.

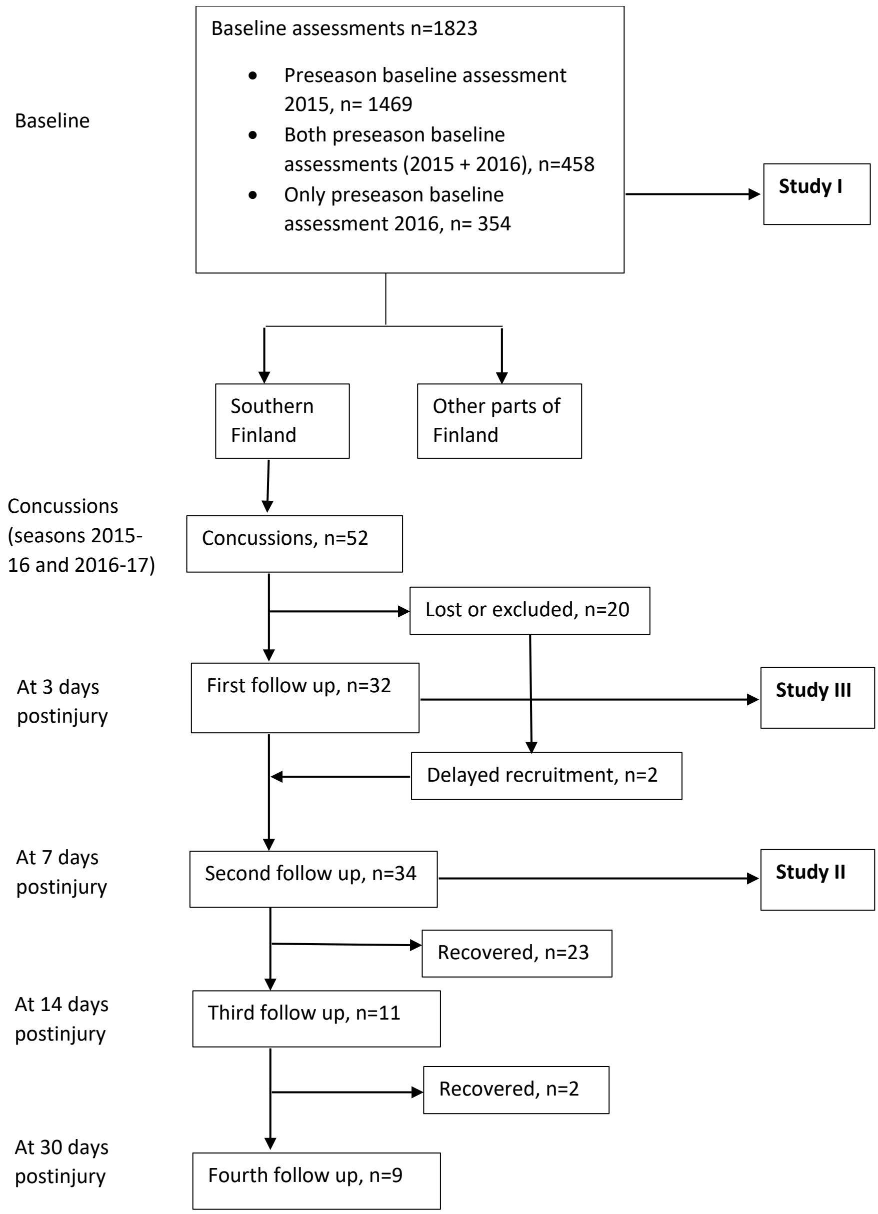


Figure 2 *Heads in the Game* baseline assessment and follow-up protocol and the selection of participants in Studies I – III.

Subjects for Study I were recruited from the 17 ice hockey clubs with elite-level junior hockey teams, providing a total of 1 823 male athletes between the ages of 12 and 21 years. They participated in baseline assessments preceding the 2015-2016 and 2016-2017 playing seasons. The baseline assessment included preseason cognitive functioning, balance, and self-reported symptom assessments. These 1 823 male athletes comprised study sample I. Athletes were divided into the learning disability (LD) group (n=108) or typical learners (n=1715) based on the presence or absence of a self-reported diagnosis of dyslexia or LD. Athletes with self-reported ADHD or ADD (n = 13) were excluded.

Study II's subjects were recruited from the 4 ice hockey clubs in Southern Finland that were selected for a more intensive follow-up at 7 days postinjury. These clubs included a total of 570 adolescent and young adult players (12-21 years of age). The clubs' medical personnel were instructed to contact the project team in the event of a suspected concussion. A total of 55 concussions in 52 athletes were reported during the 2015-2017 playing seasons. After applying the exclusion criteria (pre-existing disorder, incomplete information or second concussion during the same season), 34 subjects were included in Study II. The athletes were 14-20 years of age (*M* = 16.91, *SD* = 1.75) and had 0-4 previous concussions (*Mdn* = 0).

Study III used a subsample of 458 athletes to calculate reliable change index metrics in the first part of the study. This sample included athletes who had participated in both baseline assessments one year apart preseason 2015-2016 and 2016-2017. After applying the exclusion criteria, 312 athletes were included and comprised Study III's healthy control sample. The athletes were all male, 13-20 years of age (*M* = 16.00, *SD* = 1.52) at the time of the first baseline assessment. Study III's second part included the 4 ice hockey clubs in Southern Finland that participated in the more intensive follow-up. A total of 55 concussions in 52 athletes were reported during the two seasons 2015-2017, which formed Study III's concussion sample. Athletes participated in the follow-up assessment at day 3 postinjury. The data from the remaining 32 subjects were included after exclusion criteria. The athletes were 14-20 years of age (*M* = 16.97, *SD* = 1.73) and had 0-4 previous concussions (*Mdn* = 0).

4.2 IDENTIFICATION OF CONCUSSION AND THE ACUTE SIGNS

A concussion is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces (McCrory et al., 2013). The medical personnel employed by each team (e.g. physician, physiotherapist, or first-aid personnel) were instructed to contact the project team in case of a suspected concussion. The clubs' medical personnel identified and evaluated all suspected concussions acutely using the Sport Concussion Assessment Tool, 3rd Edition (SCAT3; Guskiewicz et al., 2013) at the time of injury. A concussion was identified when a player, after receiving a blow to the head or the body, presented with one or more somatic-, cognitive- and/or emotional symptoms (assessed with SCAT), physical signs (e.g., loss of consciousness, amnesia or disorientation as identified by on-ice examination) or behavioral change (e.g., irritability) (McCrory et al., 2013).

The teams' medical personnel were trained by the research team to identify the acute signs of concussion as well as to identify and evaluate concussion. The medical personnel carefully documented information of acute signs of concussion: loss of consciousness, amnesia, disorientation, postural instability, and vacant look. Signs of concussion were evaluated at the time of injury through observation, direct questioning, and by the athlete's self-report.

4.3 NEUROCOGNITIVE ASSESSMENT

Baseline cognitive assessment was completed before the 2015-2016, and 2016-2017 playing seasons. Concussed athletes were invited to participate in a follow-up at 3, 7, 14 and 30 days postinjury during which the measures used in the baseline assessment were readministered. The assessment was conducted in a quiet environment between the hours of 8 am and 7 pm. Cognitive functioning was evaluated with the ImPACT computerized neurocognitive test battery (Online version; ImPACT Applications Inc.). The battery consists of six individual test modules measuring attention, memory, reaction time, processing speed, learning, and executive functioning. ImPACT provides composite scores for Verbal and Visual Memory, Visual Motor Speed, Reaction Time, and Impulse Control. It also includes a Total Symptoms Score describing the severity of subjective symptoms.

Athletes also completed the SCAT sideline screening test (Sport Concussion Assessment Tool, 3rd Edition, SCAT3, Guskiewicz et al., 2013). SCAT includes the cognitive screening test Standardised Assessment of Concussion (SAC) (McCrea, 2001). SAC is a validated cognitive screening tool developed to detect the effects of concussion immediately after injury (McCrea et al., 1998). SAC is usually used at the sideline or on the day of an injury to identify cognitive deficits caused by concussion. SAC comprises four different components measuring orientation, concentration, immediate memory, and delayed memory (McCrea et al., 1998). The score from the SAC ranges from 0 to 30, and a higher score means better performance (McCrea et al., 1998).

Athletes were also evaluated with the King-Devick (K-D) test (Galetta et al., 2011). The King-Devick test is a visual performance measure of rapid number naming, which demonstrates high sensitivity and specificity in identifying concussed athletes from healthy controls (Galetta et al., 2015; Galetta et al., 2016). The K-D test is based on reading aloud a series of single digit numbers from test cards as fast as possible (Galetta et al., 2011). Test administration takes only 2 minutes (Galetta et al., 2011). The K-D test measures processing speed, visual tracking, and saccadic eye movements, and reference values are provided for Finnish ice hockey players (Vartiainen et al., 2015).

We also utilized the modified version of the Attention and Executive Function Rating Inventory (ATTEX), which is designed to identify individuals with problems in attention or in executive functioning (Klenberg, Jämsä, Häyrinen, Lahti-Nuuttila & Korkman, 2010). ATTEX is a rating scale with 55 items describing problems of inhibition, attention, and executive functioning (Klenberg et al., 2010). It was originally a teacher rating scale designed to evaluate school-aged children and adolescents in school settings (Klenberg et al., 2010), but it was modified by Liisa Klenberg to enable self-reporting in sports settings. Athletes were also assessed with the d2-R test, a computerized cancellation test that measures attention and concentration (Brickenkamp, Schmidt-Atzert & Liepmann, 2010).

4.4 STATISTICAL ANALYSIS

The IBM SPSS Statistic software versions 24.0 and 25.0 were used to perform the analysis (IBM Corp., Armonk, NY, USA). The statistical significance level was set at .05. Kolmogorov-Smirnow and Levene's tests were calculated in Study I to test that the assumptions underlying the statistical analyses were met. The independent t-test was utilized to examine whether the LD group and typical learners differed in cognitive performance as measured by ImPACT. Linear regressions with age and concussion history were performed to model neurocognitive scores in both the LD and typical learners groups. The association between LD, age and their interaction in neurocognitive performance was modeled. Linear regressions were calculated to predict the effect of LD, age and their interaction on cognitive domains assessed with ImPACT. The simple slopes analysis was employed to interpret the moderation effect. Means and SDs of ImPACT scores were calculated within each age group.

Three Study II athletes were missing baseline values, which were imputed by the average of the group values. Preliminary analyses (Kolmogorov-Smirnov and Levene's test) were calculated to ensure the statistical analyses' underlying assumptions were met. The follow-up ImPACT test scores were subtracted from the baseline scores to compare the baseline and postinjury test result. The change score was used in the series of independent samples of t-tests to assess whether the change in cognitive functioning differed between the group with and without a specific concussion sign. The athletes were divided into groups based on the presence or absence of each sign of concussion to form dichotomous independent variables. Based on the t-tests' results, hierarchical linear regression analyses were calculated to assess the association between signs of concussion and postinjury neurocognitive deficits. An a priori power analysis was conducted using G*Power3 with a medium effect size ($f2 = 0.15$) and significance level of 0.05 to estimate the adequate sample size for regression analyses. The power analysis results showed that a total sample of 55 participants was required to achieve a power of 0.80. The hierarchical linear regression analyses were done in two stages. The first stage produced the null model. The null model included no independent variables and only the control variables of age and number of previous concussions. The sign of concussion was included in the null model in the second stage to examine whether it had an effect on cognitive performance over the impact of age and number of previous concussions.

Study III used two types of analysis (the Intraclass Correlation Coefficients, ICCs and Pearson r) to estimate the reliability of the ImPACT test battery. A single measure two-way random effects analysis of variance was calculated to explore the assessment's consistency at baseline 1 and a year later at baseline 2. Paired t-tests were calculated to assess differences in scores between the two baseline evaluations. The α-level for all analyses, including the Bonferroni correction, was set at $p < .01$. Study III used the reliable change methodology to evaluate whether the change in scores between the two baseline assessments was statistically meaningful at 80 or 90% confidence intervals (CIs). The reliable change formula was used, which takes the practice effect into account (Chelune et al., 1993). The 80% CI was selected to calculate the reliable cognitive change and to analyze the effect of the on-field signs in the concussed sample. The 80% CI was used to minimize the potential of type two error and to minimize the risk of premature return to play. Chi-squared tests were calculated to examine if athletes with acute on-field signs (LOC, amnesia, disorientation, postural instability, or vacant look) would differ in the rate of cognitive decline from athletes without a sign.

5 RESULTS

5.1 ATHLETES WITH LEARNING DISABILITY DISPLAY ATYPICAL MATURATIONAL TRAJECTORIES (STUDY I)

There were 108 players who reported a diagnosed learning disability (LD) and 1715 who were defined as typical learners. The LD group obtained worse neurocognitive scores across the domains on ImPACT compared to typical learners; the performance differed in Verbal memory, [$t(1821)=4.71$, $p<.001$], in Visual memory [$t(1821)=3.55$, $p<.001$], in Visual motor speed [$t(1821)=5.89$, $p<.001$] and in Reaction time [$t(1821)= -2.69$, $p<.01$]. The LD group also reported more symptoms (Total symptoms) at baseline compared to typical learners [$t(1821)= -2.40$, $p=.02$].

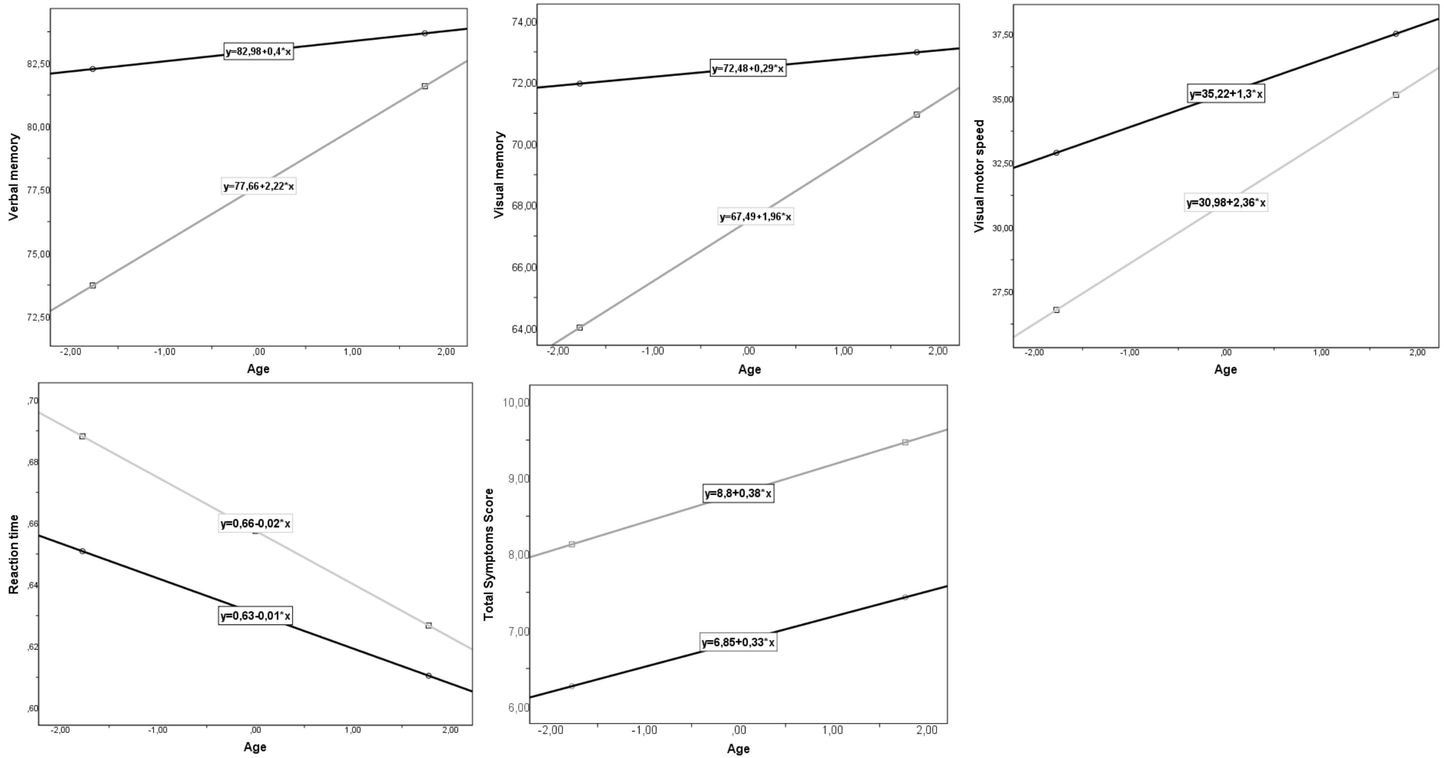
Linear regressions were calculated to predict neurocognitive scores based on age and concussion history separately in the LD and typical learner groups. The regression analysis results indicated that age significantly predicted Verbal memory, Visual motor speed and Reaction time in both groups. The concussion history did not predict any of the neurocognitive scores in either group. The original article (Study I) reports these results in more detail.

A multiple regression model was conducted to study whether the association between age and neurocognitive scores depend on the LD status. A significant interaction effect was found on verbal memory, indicating that the relationship between age and verbal memory is moderated by LD (Table 3). A simple slopes analysis revealed that there was a significant positive relationship between age and verbal memory in typical learners, $b = .40$, 95% CI [.12, .68], $t = 2.81$, $p = .01$, as well as in LD group, $b = 2.22$, 95% CI [.87, 3.57], $t = 3.23$, $p < .01$, and the effect of age was stronger in the LD group than in the typical learners (Figure 3). The significant interaction effect between age and LD was also found on visual motor speed (Table 3). The simple slopes analysis revealed a positive relationship between age and visual motor speed in typical learners, $b = 1.30$, 95% CI [1.14, 1.47], $t = 15.60$, $p < .01$, as well as in LD group, $b = 2.36$, 95% CI [1.71, 3.00], $t = 7.20$, $p < .01$, and the effect of age was stronger in the LD group than in the typical learners (Figure 3).

In summary, Study I's results show that adolescent athletes with LD obtain lower scores on neurocognitive baseline testing on ImPACT and develop at a different rate on the cognitive domains than typical learners. Atypical maturational trajectories were seen in verbal memory and in visual motor speed.

Table 3 *Linear model of predictors of verbal memory, visual memory, visual motor speed, reaction time and total symptoms. Reproduced with permission from Taylor & Francis Group, (Peltonen et al., 2018).*

	Verbal memory				Visual memory				Visual motor speed				Reaction time				Total symptoms			
	b	SE B	t	p	b	SE B	t	p	b	SE B	t	p	b	SE B	t	p	b	SE B	t	p
Constant	82.67 [82.19, 83.15]	0.24	337.82	$p<.01$	72.18 [71.58, 72.78]	0.31	234.82	$p<.01$	34.97 [34.69, 35,24]	.14	247.63	$p<.01$	.63 [.63, .64]	0.002	315.71	$p<.01$	6.97 [6.58, 7.36]	0.20	35.01	$p<.01$
LD	- 5.32 [-7.47, -3.17]	1.10	- 4.86	$p<.01$	- 4.99 [-7.73, -2.24]	1.40	- 3.57	$p<.01$	- 4.24 [-5,49, -3.00]	.63	- 6.69	$p<.01$	.02 [.01, .04]	0.009	2.94	$p<.01$	1.95 [.24, 3.66]	0.87	2.24	$p=.03$
Age	.51 [.23, .78]	0.14	3.63	$p<.01$	.39 [.04, .73]	0.17	2.22	$p=.03$	1.36 [1.21, 1.53]	.08	16.87	$p<.01$	-.01 [-.01, -.01]	0.001	-10.31	$p<.01$	.33 [.11, .56]	0.11	2.89	$p<.01$
LD x Age	1.82 [.45, 3.20]	0.70	2.60	$p=.01$	1.67 [-.08, 3.42]	0.89	1.87	$p=.06$	1.05 [.39, 1.71]	.34	3.12	$p<.01$	-.01 [-.02, .01]	0.006	-1.06	$p=.29$	.05 [-1.32, 1.41]	0.70	.07	$p=.94$
	Note. $R^2=.02$				Note. $R^2=.01$				Note. $R^2=.16$				Note. $R^2=.06$				Note. $R^2=.01$			



○ = Typical learner group

□ = LD group

Figure 3 Simple slopes equations of the regression of ImPACT composite scores on the learning disability group and on the typical learner group. Reproduced with permission from Taylor & Francis Group, (Peltonen et al., 2018).

5.2 ON-FIELD LOSS OF CONSCIOUSNESS, AMNESIA AND VACANT LOOK PREDICT COGNITIVE FUNCTIONING (STUDY II)

Study II observed the following on-field signs of concussion: disorientation in 68% of cases, postural instability in 44%, vacant look in 41%, amnesia in 27% and loss of consciousness in 24% of cases. More than one sign was reported in 65% of the cases. Figure 4 presents the occurrence and the overlap of the on-field signs.

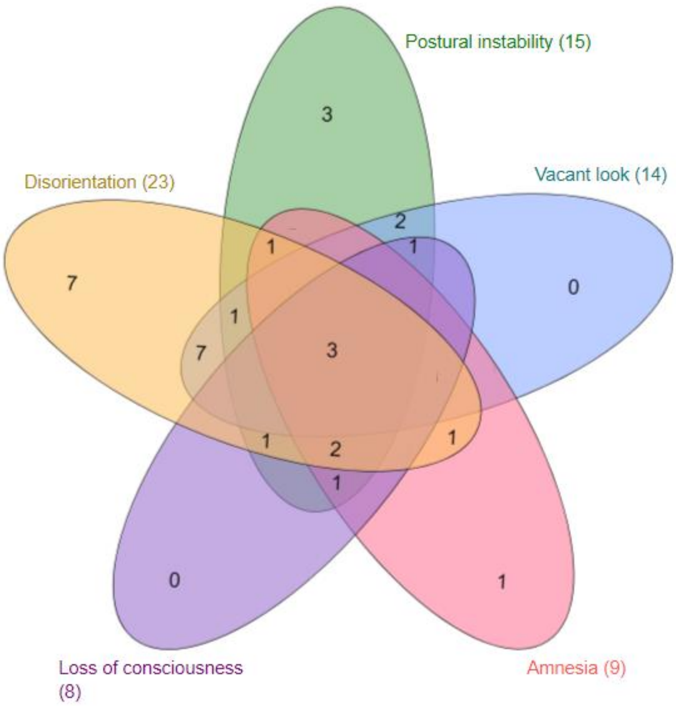


Figure 4 The overlap and frequency of on-field signs of concussion in a sample of adolescent Finnish ice hockey players (n=34).

The t-tests revealed a statistically significant group difference in verbal memory performance between the groups with or without the LOC [$t(32)=3.28$, $p < .01$] at 7 days post-injury and between the groups with or without the amnesia [$t(32)=2.54$, $p = .02$]. A significant difference was also observed in visual memory between the groups with or without the vacant look [$t(32)=2.28$, $p = .03$]. There was no significant group difference in cognitive performance between the groups with or without the disorientation or postural instability. Subjects with loss of consciousness (LOC), amnesia or the vacant look sign had larger decrements in cognition than those without these signs. Subjects with LOC, amnesia or the vacant look signs also performed worse in cognitive tests at follow-up than at baseline (Figure 5.). Further analyses were conducted to clarify the impact of loss of consciousness, amnesia, and vacant look on verbal and visual memory functioning.

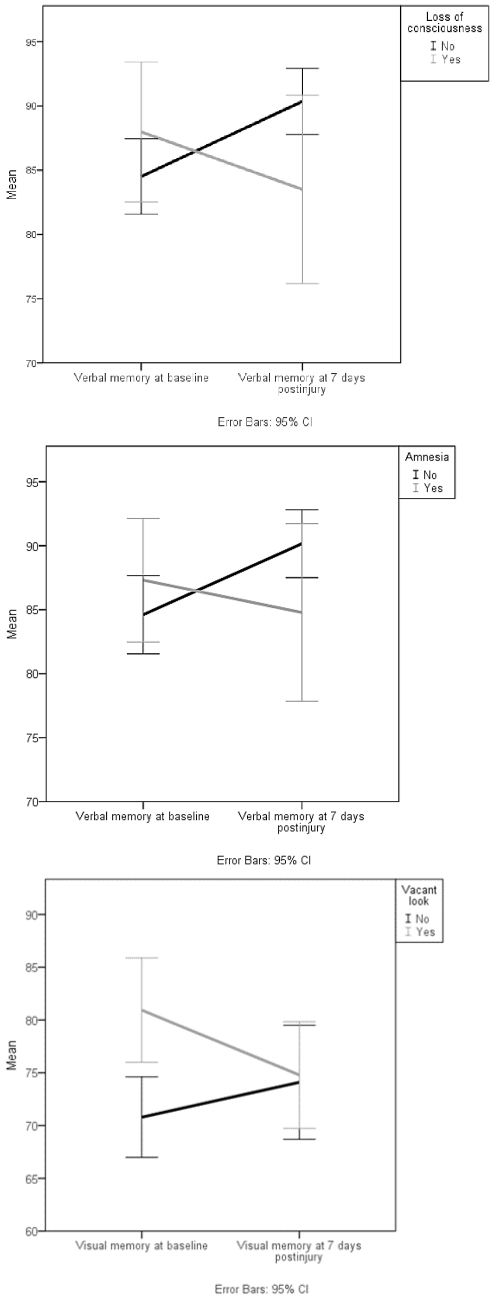


Figure 5 Comparison of verbal and visual memory performance at baseline and at 7 days postinjury in the group without the particular sign of concussion (no) and in the group with the particular on-field sign of concussion (yes) and standard error of measurements with 95% confidence interval (CI). The on-field signs were loss of consciousness, amnesia, and vacant look. Reproduced with permission from Wiley, (Peltonen et al., 2020a).

5.2.1 LOSS OF CONSCIOUSNESS

A hierarchical regression analysis was used to assess whether loss of consciousness was a significant independent predictor of change in verbal memory performance. The first step included the control variables of age and concussion history, and it was not significant, F (2, 31) =.59, p = .56. The second step added loss of consciousness to the model, and it accounted for an additional 22% of the variance in verbal memory performance, F (1, 30) = 8.96, p = .005. The three predictors accounted altogether for 26% of the variance of the change in verbal memory performance, F (3, 30) = 3.48, p = .03. Only loss of consciousness accounted for a significant proportion of unique criterion variance in the final regression model.

5.2.2 AMNESIA

The second hierarchical regression analysis was performed to evaluate whether amnesia was a significant independent predictor of change in verbal memory performance in follow up. The age and concussion history were controlled. The first step included the control variables of age and concussion history, and the results were not significant F (2, 31) =.59, p = .56. Amnesia was entered in the second step, and it accounted for an additional 15% of the variance in verbal memory performance, F (1, 30) = 5.61, p = .03. The three predictors accounted altogether for 19% of the variance in change in verbal memory performance, F (3, 30) = 2.32, p = .10, but the model was not significant. Only amnesia accounted for a significant proportion of unique criterion variance in the final regression model.

5.2.3 VACANT LOOK

The third hierarchical regression analysis assessed whether vacant look was a significant independent predictor of change in visual memory performance in follow up. The age and concussion history were controlled. The first step that included the control variables of age and concussion history was significant, F (2, 31) = 5.52, p = .01. Vacant look was entered into the model in the second step, and it accounted for an additional 9% of the variance in visual memory performance, F (1, 30) = 4.05, p = .05. The three predictors accounted altogether for a significant 35% of the variance in change in verbal memory performance, R^2 = .35, F (3, 30) = 5.39, p < .01. Vacant look and concussion history accounted for a significant proportion of unique criterion variance in the final regression model.

In summary, Study II's results indicated that on-field loss of consciousness or amnesia were associated with larger verbal memory deficits at 7 days postinjury compared to adolescent athletes without these signs. Additionally, athletes with on-field vacant look had larger decrements in visual memory performance.

5.3 POST-CONCUSSION ACUTE SIGNS AND RELIABLE COGNITIVE DECLINE (STUDY III)

For the composite scores of ImPACT, the *ICC* reliability indices ranged from 0.58 to 0.78, and for the Postconcussion Scale it was 0.43. There were significant differences in paired *t*-tests ($p \leq .01$) in all the composite scores and in the Postconcussion Scale between the baseline 1 and baseline 2 evaluation, with better performances and less reported symptoms in baseline 2. Pearson *r* correlations ranged from .39 to .71 between the baseline assessments. Reliable change indices were calculated for all composite scores and the Postconcussion Scale. Table 4 presents *RCIs* at 80% and 90% confidence intervals, the standard error of measurements (*SEMs*) and standard error of differences (*S* diff) for each of the ImPACT composites. The original article (Study III) presents more detailed results.

Table 4 *Reliable change indices (RCI) in the healthy control group n=312. Reproduced with permission from Oxford University Press, (Peltonen et al., 2020b).*

Composite	*M (SD)*		*r*	SEM_1	SEM_2	*Sdiff*	Confidence intervals	
	Time 1	Time 2					.80	.90
Verbal memory	82.83 (9.92)	84.54 (10.71)	.43	7.49	8.09	11.02	14.11	18.07
						10.59	13.56	17.37
Visual memory	70.99 (12.91)	75.13 (12.86)	.56	8.56	8.53	12.09	15.47	19.82
						12.11	15.50	19.86
Visual motor speed	34.47 (5.93)	37.22 (6.38)	.71	3.19	3.44	4.69	6.00	7.69
						4.52	5.78	7.41
Reaction time	.63 (.08)	.60 (.07)	.46	.06	.05	.08	0.10	0.13
						.08	0.11	0.14
Postconcussion Scale	7.29 (8.42)	3.41 (4.31)	.39	6.58	3.37	7.39	9.46	12.12
						9.30	11.90	15.25

S diff, standard error of difference scores based on Chelune et al. (1993), upper row, $\sqrt{([SEM_1^2]+[SEM_2^2])}$; and Jacobson and Truax,(1991) lower row, $\sqrt{(2*[SEM_1^2])}$.

The number of scores that reliably changed from baseline to postinjury evaluation for each subject was then computed in the concussed sample. The 80% confidence interval was selected as the cut point to estimate the reliable decline as follows: Verbal Memory ≥ 14 points, Visual Memory ≥ 15 points, Visual Motor Speed ≥ 6 points, Reaction Time ≥ .10 s, and Postconcussion Scale ≥ 9 points. The percentages of athletes with concussions showing declines across the five composite scores at day 3 postinjury were no declines = 56%, one decline = 25%, two declines = 16%, three declines = 0%, four declines = 3%, and five declines = 0%. Athletes with concussions were much more likely to have two or more declines across the five composites than the subjects in the healthy sample [$X^2(1) = 19.48$, $p = .00001$; *Odds Ratio* = 8.77, 95% *CI* = 2.83–27.19].

A comparison between the groups with and without an acute sign of concussion (loss of consciousness, amnesia, disorientation, postural instability, or vacant look) revealed that the athletes with loss of consciousness, amnesia or postural instability were more likely to have two or more declines across 5 composites than subjects without this sign (Table 5). In contrast, the group with acute disorientation and the group with acute vacant look did not differ in the number of cognitive declines from the groups without these signs (Table 5).

Table 5 *Chi square and Odds ratio for having 2 or more declines on ImPACT in the concussion sample (n=32). Many athletes showed more than one sign. Reproduced with permission from Oxford University Press, (Peltonen et al., 2020b).*

Sign	Present (%)	Absent (%)	Chi square	Odds ratio (*OR*)	*OR* 95% *CI*
Loss of consciousness	6 (18.75)	26 (81.25)	4.73, p < .05	7.67, p < .05	1.04–56.77
Amnesia	6 (18.75)	26 (81.25)	4.73, p < .05	7.67, p < .05	1.04–56.77
Disorientation	22 (68.75)	10 (31.25)	.02, p = .90	.89, p = .45	.13–5.89
Postural instability	15 (46.88)	17 (53.13)	3.94, p < .05	8.00, p < .05	.81–78.83
Vacant look	14 (43.75)	18 (56.25)	1.58, p = .21	3.20, p = .11	.49–20.81

In summary, Study III's results indicated that, after controlling the measurement error and learning effect in performance, the adolescent athletes with acute loss of consciousness, amnesia or postural instability were approximately 8 times more likely to have 2 or more declines across the 5 ImPACT composite scores 3 days postinjury than those without the sign.

6 DISCUSSION

The present study examined neurocognitive performance of adolescent Finnish athletes in a nationwide cross-sectional sample of ice hockey players. We assessed athletes' neurocognitive functioning in the healthy and concussed samples. Concussive injuries and on-field signs of concussion were carefully identified and documented in games and practices during the 2015-2017 playing seasons, and the athletes were assessed serially postinjury.

Athletes with learning disability (LD) performed worse on neurocognitive baseline assessments compared to typical learners, and atypical maturational trajectories were observed in verbal memory and in visual motor speed. The first Finnish normative values concerning adolescent athletes were published for ImPACT in typical learners and athletes with LD separately. The usefulness of on-field signs of concussion (loss of consciousness (LOC), amnesia, disorientation, postural instability, and vacant look) for predicting postinjury neurocognitive decline were examined using regression-based and RCI methodology. From the on-field signs of concussion, only disorientation did not predict the postinjury neurocognitive decline in the present study. The findings validate the importance of on-field LOC, amnesia, postural instability, and vacant look for predicting postinjury neurocognitive decline.

6.1 THE EFFECT OF AGE, CONCUSSION HISTORY AND LD ON NEUROCOGNITIVE PERFORMANCE IN YOUTH

We explored the interaction of age, concussion history and self-reported LD on neurocognitive performance at baseline in Study I. The findings indicated that athletes with LD have a lower neurocognitive performance in the ImPACT test at baseline compared to typical learners. Athletes with LD also developed at a different rate in several areas of cognition compared to typical learners. Contrary to our hypothesis, the number of concussions together with the LD did not cumulatively impair neurocognitive functioning at the baseline. The findings are in line with prior research showing that children with LD have deficits in cognitive skills. LD has been especially associated with deficits in short-term memory (Moll, Göbel, Gooch, Landerl & Snowling, 2014). Masoura and colleagues (2020) explored working memory skills in children with reading difficulties compared to children with typical reading skills. They assessed the four components of the working memory (the model by Baddeley and Hitch 1974 and revised by Baddeley 2000): the phonological loop, visuo-spatial sketchpad, episodic buffer, and central executive. The findings of Masoura and colleagues (2020) indicated that children with reading difficulties performed worse in all domains of working memory compared to their counterparts except visual-spatial short-term memory. A meta-analysis also showed a clear association between mathematical difficulties (dyscalculia) and working memory deficits (Peng, Namkung, Barnes & Sun, 2016). Learning disabilities have also been associated with deficits in processing speed and executive functioning (Bonifacci & Snowling, 2008; Bull & Johnston, 1997; Catts, Gillispie, Leonard, Kail & Miller, 2002; Silver et al., 2008). The just-mentioned studies are consistent with Study I's findings. The concussion history was not associated with baseline neurocognitive performance in this study. This finding might reflect the limited power of this study while only under 4% of participants reported a history of 3 or more concussions.

Study I's LD group obtained lower scores on verbal and visual memory, visual motor speed and reaction time than typical learners, and maturational trajectories in verbal memory and visual motor speed differed between these two groups. There are two contradicting models that could potentially explain the differing maturational trajectories: the developmental lag and the deficit theory (Francis et al., 1996). These two theories have different hypotheses of the underlying neurobiology of LD. The lag model says that children with LD are thought to vary from their peers only in the rate at which their cognitive skills develop, and they would catch up with others as their brains mature (Francis et al., 1996). It is hypothesized in the deficit model that the brain organization in LD is disordered and that no catching up will occur (Rourke, 1976). The "catching up" was observed in verbal memory and in visual motor speed in Study I but not in other domains of ImPACT. The LD group also reported more subjective symptoms at the baseline compared to typical learners, as reported in previous studies (Elbin et al., 2013; Zuckerman et al., 2013).

The ImPACT is a prompt cognitive assessment method designed to assess cognitive deficits after concussion. The problem with cognitive psychometric measures is that they usually lack sensitivity when individuals with extremely high or low cognitive capacity are compared with normative data (Rabinowitz & Arnett, 2012; Schatz & Robertshaw, 2014). For example, athletes with LD are more likely to have an exceptionally poor baseline score on ImPACT (Schatz, Moser, Solomon, Ott & Karpf, 2012), which could be misinterpreted as "sandbagging," not trying their best, and invalid. Normative data are relied on in interpreting the post-injury results in the absence of baseline data. Comparing an athlete with LD solely on normative data in a postinjury assessment can lead to false positives and delayed return to play because of the lower cognitive scores due to LD. The optimal spacing between baseline assessments might be shorter in the LD group than in typical learners because of the differing rate of cognitive development in adolescence shown in Study I. Based on their rapid cognitive development, yearly baseline testing is recommended for young athletes and athletes with LD (Hunt & Ferrera, 2009; Reynolds et al., 2016).

6.2 ON-FIELD SIGNS OF CONCUSSION PREDICT THE CHANGE IN NEUROCOGNITIVE PERFORMANCE POSTINJURY: LOC, AMNESIA, AND VACANT LOOK

Study II assessed on-field signs (LOC, amnesia, disorientation, postural instability, and vacant look) as predictors for change in neurocognitive performance in concussed athletes at 7 days postinjury. Study II's main finding was that LOC and amnesia were associated with more pronounced verbal memory deficits when compared to concussed athletes without these signs. LOC and amnesia have traditionally been important markers of concussion in the prognosis of severe brain injuries, but their usefulness in milder brain injuries has been questioned. Iverson and colleagues (2017) pointed out in a systematic review that most studies have not found an association between LOC or posttraumatic amnesia (PTA) and worse clinical outcomes, even if some studies have shown this relationship. The duration of on-field LOC, amnesia or disorientation lasted longer than 5 minutes in a study in which the association was found (Lovell et al., 2003). However, disorientation was not associated with cognitive deficits at 7 days postinjury in the present study. Based on Study II's results, an athlete's memory functioning should be carefully assessed postinjury. LOC and amnesia are also important on-field signs that might be useful in predicting cognitive clinical outcomes in adolescent athletes.

Study II revealed that an on-field vacant look was associated with larger decrements in visual memory performance when compared to athletes without this sign. Vacant look has been considered a subjective sign because it is heavily dependent on a rater's own view. However, vacant look has a high specificity for a diagnosis of concussion when the sign is identified properly (Makdissi & Davis, 2016). Study II found that an on-field vacant look was observed in 41% of injuries, and it always co-occurred with another sign or signs, most often with disorientation, and was not present alone in any of the cases (Figure 4). The vacant look-sign is challenging to identify (Makdissi & Davis, 2016), so it might be that it is more easily missed if it is present as the only on-field sign of concussion. LOC was another sign that did not occur alone but always with several other signs (Figure 4). This observation might suggest that the presence of LOC is associated with a number of other symptoms. Three out of 34 (8%) concussed participants had all 5 acute on-field signs of concussion, and all of them either performed worse (-1 to -3 *SD*) in verbal memory, reaction time or reported more symptoms compared to other participants. One of these athletes with all signs showed evident reliable cognitive decline using the Finnish reliable change scores published in Study III.

The most common on-field sign was disorientation, present in 68% of injuries, which was a higher percentage compared to other studies (Guskiewicz et al., 2000; Lovell et al., 2003). The prevalence of LOC (24%) was also much higher than reported in previous studies that focused mainly on collegiate and high school athletes (Harmon et al., 2013; McCrea et al., 2020). It is unlikely that concussions occur more prominently in Finnish youth ice hockey compared to other nationalities. Instead, head injuries with LOC might have been more easily recognized than injuries without this sign.

6.3 ASSOCIATION BETWEEN POSTCONCUSSION ACUTE SIGNS AND RELIABLE NEUROCOGNITIVE DECLINE

The change in neurocognitive test scores can be analyzed using different statistical methods. T-tests and analysis of variance are popular in human sciences to determine group differences. These are efficient in describing overall trends, but they are limited in interpreting meaningful individual change that would help clinicians' decision making (Parsons, Notebaert, Shields & Guskiewicz, 2009). Reliable Change Indices (RCI) methodology is used to calculate individually meaningful change between repeated measurements (Jacobson & Truax,1991). We applied the reliable change methodology in Study III to the concussed sample of athletes to further examine the association between acute on-field signs of concussion and neurocognitive deficits at 3 days postinjury. Study III's main findings showed that athletes with acute on-field LOC, amnesia or postural instability had an approximately eight-fold increased risk of declines in 2 or more cognitive areas assessed with ImPACT. These findings highlight the importance of postural instability as an on-field sign predicting postinjury cognitive decline. Brett and colleagues (2018) examined the association between acute on-field, objective signs and symptoms reported within 1 day postinjury. They observed that on-field memory deficit and postural instability predicted a greater likelihood of endorsing self-reported cognitive-migraine-fatigue symptoms within 1 day postinjury (Brett et al., 2018). An on-field memory deficit was correlated with two symptoms: trouble remembering and concentration difficulties (Brett et al., 2018). Postural instability was related to symptom endorsement of trouble remembering (Brett et al., 2018). The present study's findings suggest that the presence of on-field LOC, amnesia or postural instability may indicate a more severe injury. Our findings are in line with the idea that concussion management protocols should include both neurocognitive and postural stability testing (McCrory et al., 2013).

Reliability estimates were calculated from a healthy control sample of adolescent Finnish athletes to assess the reliability of the Finnish version of ImPACT. Test-retest reliability (*r*) for ImPACT composites scores ranged from .39 to .71. These reliability estimates for ImPACT composite scores were in line with those of Bruce and colleagues (2014) that ranged from .46-.76. and were derived from a multilingual sample of professional ice hockey players. However, the correlation coefficients in the present study were considerably lower compared to the reliability indices ranging from .65-.86 reported by

Iverson and colleagues (2003) from a sample of English-speaking athletes from the USA. Different reliability values for ImPACT have been published depending on the time interval between the tests and the athletes' linguistic origin (Bruce, Echemendia, Meeuwisse, Comper & Sisco, 2014; Tsushima, Siu, Pearce, Zhang & Oshiro, 2016). There is no consensus on the proper time interval to estimate the test-retest reliability. Iverson and coworkers (2003) used the 1-week time interval between the tests, while we used a 1-year interval to reflect the real-world situation, because the vast majority of concussions occur months to years after baseline testing rather than within days. Additional possible factors explaining the variability in reliability values could be the lack of equivalence of these translations and differing validity and overall psychometric properties of each test version.

RCIs were calculated in Study III for ImPACT scores based on the healthy sample. The reliable cognitive decline in a Finnish sample was defined as follows: verbal memory ≥ 14 points, visual memory ≥ 15 points, reaction time ≥ .10 s, visual motor speed ≥ 6 points, and Postconcussion Scale ≥ 9 points. Larger changes in between the baseline and postinjury composite scores were required for a reliable change in the Finnish sample compared to the sample from the USA (Iverson et al., 2003). The present study's results do not support the blind use of ImPACT with English normative data for multilingual populations. Study III provided reliable change scores that can be utilized in the Finnish population and clinical settings and provided valuable information about cross-national differences in neurocognitive evaluation.

6.4 STRENGTHS AND LIMITATIONS OF THE STUDIES

A clear strength of the present study was its large nation-wide sample. All subjects underwent a preseason neurocognitive baseline assessment that permitted the comparison of postinjury test results to a preinjury baseline. Predefined, clear criteria for suspicion of concussion and concussion management protocols were used in the present study. Validated cognitive assessment methods were used in the prospective study setting. This was the first study to explore the 1-year test-retest reliability of the Finnish version of ImPACT with a large nationwide sample and to provide reliable change scores that might have clinical utility in the Finnish population. This project introduced the structured concussion assessment and recovery monitoring program and provided information about concussions to the ice hockey clubs. An obvious strength of the present study was the applicability of its findings to real life situations.

There are some limitations worth noting. Study I used cross-sectional sampling instead of a longitudinal design that would have been better for detecting age-related cognitive development during adolescence. Only 6% of athletes reported LD in Study I, which might be an underestimation. Data about LD gathered from clinical interviews, objective academic testing or parent reports might have been more reliable than the self- report we used (McKay, Schneider, Brooks, Mrazik, & Emery, 2014). The specific type and severity of learning disabilities were not further examined. The findings are not directly generalizable to individuals with other developmental disorders, such as ADD or ADHD, while these conditions were excluded from the data (n=13). Our sample, consisting of the baseline assessments, was collected nationwide, whereas the sample size of concussed athletes in Studies II and III were notably small, which limits the generalizability of the findings. Therefore, we also could not include LD status as a variable in the models. The duration of on-field signs, such as LOC or amnesia, was unfortunately not known in the concussed sample. The team's medical personnel were trained to identify on-field signs of concussion, but no fidelity or interrater reliability checks were performed. Brain imaging was not done systematically and if done, the data were unavailable for analysis. All subjects were male ice hockey players, which may limit the generalizability of the findings to other populations.

6.5 GENERAL DISCUSSION

Concussion is a common injury in high velocity sports. A total of 52 (9.1%) of the 570 participants were reported concussed during the 2015-2016 and 2016-2017 ice hockey seasons in the present study. The athletes were all in the age levels that permitted checking. Kontos and colleagues (2016) have reported similar incidence rates for youth ice hockey in similar age bands. They examined the incidence of concussion in a sample of 397 youth ice hockey players aged 12-18 (Kontos et al., 2016). Their study found that a total of 37 (9.3%) of the participants incurred a diagnosed concussion during the 2012-2013 and 2013-2014 youth ice hockey seasons (Kontos et al., 2016). They reported the incidence rate for games and practices as 1.58 concussions per 1000 athletic exposures and younger athletes having higher incidence rates than older athletes (Kontos et al., 2016). This rate might also reflect the concussion incidence rate in Finnish youth hockey.

Concussions are complex injuries. The evaluation and management of concussion requires a multifaceted approach and team. Neuropsychological assessment is an essential part of the concussion evaluation (Kontos et al., 2016). Neuropsychologists have special expertise in the evaluation of athletes' cognition, behavior, and social-emotional functioning both pre- and postinjury (Echemendia & Gioa, 2018). There are special challenges in the management of concussion in youth. It is important to acknowledge that adolescent athletes are prone to thinking of short-term consequences only, underreporting their symptoms, and engaging in risk-taking behaviors due to their developing cognitive, social, and emotional skills. Neuropsychologists can provide psychoeducation to young athletes, help them to cope with their emerging emotions, give support in the treatment of symptoms and assist in their gradual return to play and to school (Echemendia & Gioa, 2018).

LD and concussion share many common features, which makes diagnosing and managing concussions difficult in athletes with LD. Athletes with LD may also be more prone to concussions (Collins et al., 1999; Nelson et al., 2016). A study showed that multiple concussions can cause additional cognitive deficit in athletes with LD compared to typical learners (Collins et al., 1999). Athletes with LD who sustain a concussion might have less brain reserve capacity than athletes without LD (Collins et al., 1999). Athletes with LD have difficulties with academic skills, and their academic performance might decline even more due to the concussion (Collins et al., 1999). Concussed athletes should have a possibility of having modifications to their academic curriculum. Special attention should be given to the planning and intervention policies regarding return to school for athletes with LD (Iverson et al., 2017). The present study's findings are in line with the recommendation that a neuropsychologist is warranted to perform and interpret the results of the neurocognitive evaluation of athletes with LD or behavioral disorders (Karlin, 2011).

There might be some cultural effect seen in the reliability estimates of the Finnish version of ImPACT. An earlier study found that Finnish adult ice hockey players perform slower in speed-related measures of ImPACT compared to the English-speaking sample but faster compared to the Czech-speaking sample (Vartiainen et al., 2019). Daugherty and colleagues (2017) examined how the use of North American neuropsychological tests affects the diagnostic accuracy of cognitive disorders in a group of culturally diverse individuals. Their findings revealed that diagnostic errors occurred 20% of the time, and the frequency of errors varied by nationality (Daugherty et al., 2017). They concluded that using cognitive assessment methods from one culture to assess subjects from other cultures produces significant false positives (Daugherty et al., 2017). The Finnish translation of ImPACT has long been available, but there is a lack of studies examining its psychometric properties. This was the first study to examine 1-year test-retest reliable estimates for the Finnish test version of ImPACT. The findings highlight the importance of using language-specific normative values and reliable change estimates in concussion assessments. More studies are warranted to examine the reliability and validity of different language versions of ImPACT.

6.6 CONCLUSIONS

We explored the interaction effects of age, LD, and previous concussion history on baseline cognitive performance in adolescent Finnish athletes. Contrary to our expectations, concussion history did not predict any of the neurocognitive scores of ImPACT at the baseline. However, age significantly predicted most of the neurocognitive scores in ImPACT. The significant interaction effect between age and LD on both verbal memory and visual motor speed were observed. These findings indicated that LD status affected the development of verbal memory and visual motors speed. We also examined the usefulness of on-field signs of concussion (i.e., LOC, amnesia, disorientation, postural instability, and vacant look) for predicting worse-than-baseline neurocognitive performance during the acute post-injury period in youth athletes. On-field LOC, amnesia and vacant look were associated with larger deficits in memory compared to concussed adolescent athletes without these signs. We explored further the association between on-field signs and the rate of acute neurocognitive decline using RCI methodology to determine whether the cognitive decline is individually meaningful. Based on our findings, athletes with on-field LOC, amnesia, or postural instability were approximately 8 times more likely to have impairments in 2 or more cognitive areas evaluated by ImPACT at 3 days postinjury.

The present study's findings encourage conducting individual baseline testing in populations with a large variation in cognitive performance, such as in youth athletes and athletes with LD. The published reference values of adolescents and young adults provide practical data for clinicians that may have utility in concussion management of athletes without individual baseline data. Concussed adolescent athletes with on-field LOC, amnesia, postural instability, or vacant look are at risk of having postinjury cognitive deficits. Postinjury cognitive functioning should be carefully assessed and monitored before a gradual return to sports. Memory functioning is especially sensitive to concussion and should be carefully assessed. The reliability estimates and RCIs in the present study differed from those published previously from the English-speaking samples, highlighting the importance of language- and culture-specific reference values.

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